Abstract

On Recent Behavioral DSGE Models

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With growing interest in the view that macroeconomics should incorporate departures from rationality, many economists have attempted to explain the economy by careful observation of individuals' behavior. It is often assumed in standard macroeconomics that firms face fixed costs of changing prices that lead to sticky prices. Marketing surveys reveal, however, that the primary reason firms keep their prices rigid is due to the concern of antagonizing and thus losing their customers. In this paper we study recent behavioral economic models, in particular behavioral Dynamic Stochastic General Equilibrium (DSGE) models. To investigate the fitness of these behavioral price-setting models into the real economy, we estimate the log-linearized version of the behavioral price setting model from Rotemberg (2005) using Bayesian estimation methods. Then we compare the obtained estimation results to the

Bayesian estimation results of the standard New Keynesian 3 equation model. The comparison of estimated results to the results of the standard New Keynesian model allowed us to conclude that when the steady state rate of inflation equals zero, the behavioral model and the standard New Keynesian model display similar impulse response patterns, albeit they exhibit some differences in the magnitude of the response. Moreover, when the steady state rate of inflation is positive, the behavioral and the standard New Keynesian model display strikingly similar impulse responses.

Keywords: Behavioral DSGE; Fair Pricing; Customer Anger; Altruism Parameter; Calvo Price Setting; Bayesian Estimation.

Student Number: 2010-23020

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1 Introduction

It seemed, at least until the eruption of the financial crisis in 2007, as if macroeconomics had reached its zenith of success. The economy of the industrial world was experiencing macroeconomic stability with low and stable inflation, high and prolonged economic growth, and stability in many economic and financial variables. There was a general consensus among economists that the cause of this economic moderation was at least in part due to the new insights provided by modern macroeconomic theory. In this theory, a rational agent continuously optimizes his utility using all information that is available to him. Despite their rational optimization, individual agents sometimes do make mistakes. However, they do not make systematic mistakes, and as a consequence, stability is brought to the economy. Although there was an agreement that macroeconomic variables could be subjected to large changes, the causes of these large changes were always attributed to sources outside the world of rational agents. Thus, the economy was modeled as a world that was regularly hit by an exogenous shock, but where rational individuals had a complete understanding of the world and continuously strived to make optimal decisions.

To some degree, the financial and economic upheavals following the crash in the US subprime market have undermined this view of fully rational and informed agents, and its subsequent economic stability. Instead, the view that macroeconomics should incorporate departures from rationality began to gain attention. With growing interest in departures from rationality, many economists attempted to explain the economy by careful observation of individuals' behavior.

The goal of this paper is to study recent behavioral economic models, in particular behavioral Dynamic Stochastic General Equilibrium (DSGE) models. In macroeconomics, it is often assumed that firms face a fixed cost of changing prices that lead to sticky prices. Marketing surveys reveal, however, that the primary reason firms keep their prices rigid is due to the concern of antagonizing and thus losing their customers. This literature had been previously covered by Rotemberg (2005), who introduces the concept of altruism and fair pricing. Specifically, using the information about the firm's marginal cost, consumers assess whether a price increase is "fair". For instance, if the amount of price increase is larger than the corresponding increase in marginal cost, consumers will view this price increase as unfair, which triggers consumers' anger. This will lead to a sharp decline in sales, and therefore, in order to avoid consumers' anger, firms will keep their prices stable.

Similarly, in his more recent work, Rotemberg (2010) introduces the concept of "consumer regret". Observing an increase in price of a storable good, consumer shows regret for not having purchased more of it in advance. In an attempt to appear altruistic to their consumers, firms internalize this consumer regret into their cost function. This kind of modeling generates a result akin to menu cost model, and produces nominal stickiness.

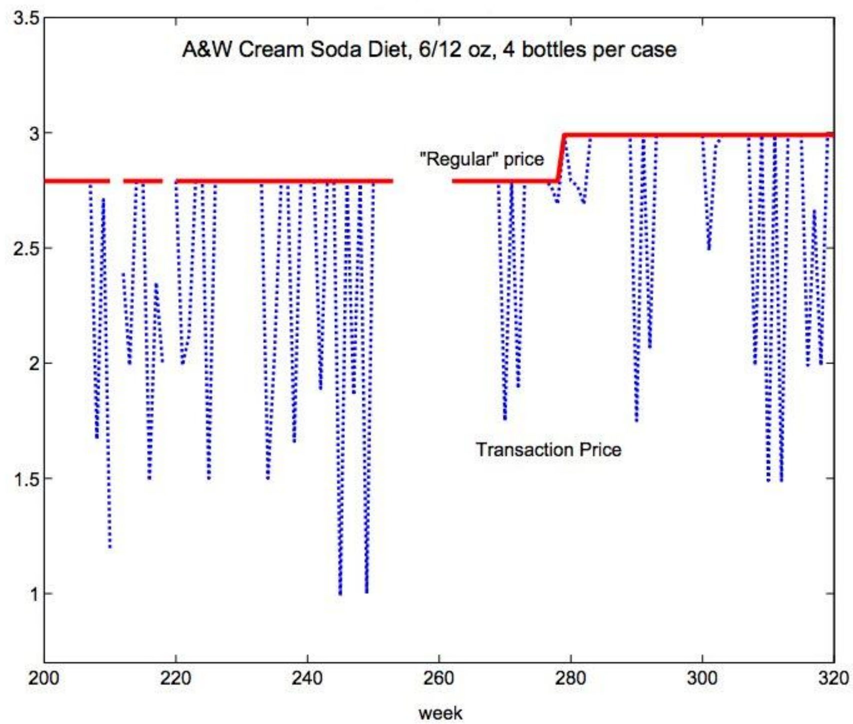
In this paper, I introduce several existing behavioral price-setting models. To investigate the fitness of these behavioral price-setting models into the real economy, I estimate the log-linearized version of the behavioral price setting model from Rotemberg (2005) using Bayesian estimation method. Then I compare the obtained estimation results to the Bayesian estimation results of a basic New Keynesian model.

The paper proceeds as follows. The next section briefly covers related literature on sticky prices for behavioral and non-behavioral models. Section 3 presents the behavioral pricing model from Rotemberg (2005). Section 4 then analyzes and compares the estimated results of the behavioral and the standard new Keynesian model, and section 5 concludes.

2 Literature Review

2.1 Non-Behavioral Price Setting

The size of the real effects of monetary policy on the economy is the central issue in monetary policy analysis. With the availability of micro-level data, recently there has been a surge of empirical work to study this issue. One of the key factors used in these studies to examine to size of the real effects of monetary policy is the frequency of price changes. Monetary policy's real effects on the economy depend crucially on the stickiness of prices. If price series exhibit frequent price changes, then monetary policy shock will have only small real effects. In contrast, if prices change infrequently, the monetary shock will have significant real effects. However, the frequency of the price change in the data crucially depends on how sales are treated in the data since a sizable fraction of price changes in the data are sales.



Source: P. Kehoe and V. Midrigan, "Sales and the Real Effects of Monetary Policy," Working Paper 652, 2007

Figure 1: Example of price series

Figure 1 shows a typical price series, namely the price of a six-pack of Diet A&W Cream Soda. All periods in which the dashed line does not equal the solid line are defined to be sales. This figure makes clear that sales are frequent while other types of price changes are rare. Excluding sales excludes most of the price changes in the original price series. Another fact that we can note from this figure is that price changes are large and the price changes tend to spend a lot of time at only a couple of values. This pattern is an archetype of retail pricing. As already mentioned, monetary policy's real effects on the economy depend crucially on the rigidity of prices. In this sense, figure 1 poses a conundrum because the price path displays great flexibility on the one hand, but also exhibits substantial stickiness on the other. Two most widely used methods of dealing with sales are the *take-sales-out* approach and the *leave-sales-in* approach. Take-sales-out approach excludes sales from the data, writes down a model without sales, and then matches the frequency of price changes to the data with sales excluded. The leave-sales-in approach includes sales in the data, writes down a model-without sales, and then matches the frequency of price changes to the data with sales included. Sale is treated just like any other price change in the leave-sales-in approach, whereas a sale is treated as no price change in the take-sales-out approach. Kehoe and Midrigan extend existing sticky price models by adding a motive for sales and show that the model can explain most of the patterns of sales in the data. Moreover, they evaluate the existing approaches and document that neither approximates well the real effects of money in an economy where sales are explicitly modeled.

Nakamura and Steinsson (2008) analyzed the nature of price setting by using Bureau of Labor Statistics (BLS) microdata, and documented the empirical characteristics of the different types of price changes in the U.S. economy. They focus on the price changes generated by temporary sales and shed light on the question of whether the macroeconomic implication of price rigidity is determined by the relative frequency of different types of price changes. One of their key findings from the U.S. data is that sale price changes display significantly different empirical features compared to regular price changes, in a sense that sale price changes are much more transient than regular price changes. By excluding sales from the definition of price changes, they document a price change of approximately 8 to 11 months. Bils and Klenow (2004), in contrast, treat sales as any other price change in the data and document that price changes about every 4.3 months. This conclusion shows that when sales are included in the data, prices are flexible, whereas prices are sticky when sales are excluded. Another interesting feature of the price change documented by Nakamura and Steinsson is that the frequency of price increases strongly covary with the inflation rate, whereas the frequency of price decreases and the size of price changes do not. Moreover, price adjustments exhibit seasonality, and one-third of non-sale price changes are price decreases.

To address the issue of whether nominal rigidities are important for macroeconomists, Eichenbaum et al (2009) have conducted an empirical work using weekly scanner data set and documented that nominal rigidities do not necessarily take the form of sticky prices. Instead, they found out that nominal rigidities take the form of inertia in reference prices and costs. Reference prices (costs) are defined as the most often quoted price (cost) within a given time period. The duration of reference prices and costs turns out to be much more inertial compared to weekly prices and costs. Related literature on nominal rigidities has generally assumed that these rigidities exhibit the form of sticky prices, and that the prices do not respond rapidly to shocks. Eichenbaum et al (2009), however, reveal that there exists significant persistence in reference prices and costs and thus display a type of rigidity that is not present in conventional macroeconomic models.

In line with Eichenbaum et al (2009), in order to investigate whether and how to incorporate temporary price reductions into models of price setting, and whether price changes due to sales have implications for theories of monetary neutrality, Chevalier and Kashyap (2011) explore retailers' strategic price-discrimination for price determination in the presence of heterogeneous consumers. They model two types of consumers, "loyals" who buy only one brand and do not strategically time purchases, and "bargain hunters" who shop for low-priced products both across brands and across time. They show that in this setting, retailers optimally choose long periods of constant regular prices disturbed by frequent temporary sales. They also show that the effective price paid is approximated by a weighted average of the fixed weight average list price and the lowest price available, namely the "best price". These results suggest that sales are important even for macroeconomists, and that sales should not be neglected.

2.2 Behavioral Aspects of Price Setting

According to canonical economic literature, consumers make effective use of price information to maximize their consumption-based utility subject to the constraint that the total value of their purchases cannot exceed their income. In other words, in the standard economics analysis, consumers view prices as mere incentives to guide their purchases. Some consumers, however, appear to display unsophisticated behavior when using price information to plan their consumptions. Consumers' imperfect rationality is a departure from the cognitive assumptions of standard economic analysis, but can nevertheless explain a number economic phenomena, including price rigidity.

Consumers sometimes display emotional reactions to price changes, such as anger and regret. Moreover, as opposed to being purely selfish, consumers' welfare is sometimes affected by the welfare of others. According to Blinder et al (1998) and Fabiani et al (2006), when firms are asked why they keep their prices rigid, their reply was that they do so in order to avoid angering their customers. In line with this observation, Rotemberg (2011) constructs a model where firms act as if they were altruistic in order to avoid triggering consumers' anger. If customers deem firms to be insufficiently benevolent towards them, they might respond negatively by not purchasing the product from the firm. Therefore, in order to avoid these negative reactions, firms have no choice but to internalize customers' emotions. The firm's desire to appear altruistic towards the consumers can lead them to adopt third-degree price discrimination based on the income differences of consumer classes while forswearing third-degree price discrimination that is based on the differences in the elasticity of demand. This model can also explain why prices show greater response to changes in factor costs than to changes in demand, despite the fact that their impact on the marginal cost is the same.

Furthermore, in order to avoid antagonizing their customers, firms have to internalize the regret and disappointment that customers experience when the price that they face is higher than a price that was available to them previously. Regret greatly matters in consumers' decision making. People's desire to avoid confronting regrets and blaming themselves for undesirable outcomes leads them to change their course of action.

If the price of a storable good increases, customers regret not having purchased the product earlier. Likewise, customers show regret for not having waited if they notice a price decrease. Although most of the formal literature deriving price rigidity has put emphasis on administrative menu costs, Rotemberg (2010) analyzes firms' price changing pattern when they empathize with the regret costs of their consumers.

An interesting evidence of this argument is reported from an experimental comparison of two treatment groups. In one treatment, individuals are not informed about what would have happened under an alternative course of action, whereas they are informed in the other treatment. Cooke et al (2001) report a case where subjects are faced with a sequence of price offers and must make a purchase. In one treatment group, subjects do not see offers after they make a purchase while they do in the second treatment group. In an attempt to avoid the regret of paying "too much", subjects were less inclined to make a purchase in the treatment where they continued to see offers after the purchase.

Both regret and anger are emotions that are triggered when people realize that they are worse off than they could have been. One difference between regret and anger is that, in the case of anger, someone else is blamed for the undesirable outcome. According to Berkowitz and Harmon-Jones (2004), anger is "linked associatively with an urge to injure some target". In terms of the traditional utility, angry people's utility increases when the target of their anger is injured or harmed. As an illustrative example, when Apple reduced the price of iPhone by $200 in September 5, 2007, many customers who had bought the product before the price reduction posted many angry messages. When Kahneman, Knetch and Thaler (1986) asked their respondents whether they deem it as fair for a store to raise the price of its snow shovels after a snow storm from $15 to $20, approximately 80 percent of the respondents viewed it as either “unfair” or “very unfair”.

One interesting theory by Kahneman, Knetsch and Thaler (1986) is that consumers feel that they are entitled to their “reference transaction”, while firms are entitled to their “reference” level of profits. By reference transaction and profits, they refer to past offers made by the firm and the firms’ past profits. In this sense, consumers are entitled to the same price of a snow shovel as before the storm because the firm’s profits will not decline even the prices are kept constant. Likewise, price increases that are accompanies by cost increases are viewed as fair because, although consumers can no longer access their reference transactions, firms come closer at maintaining their reference profit levels.

Several marketing studies show that customers engage in very little product comparison on a typical shopping trip. In his recent paper, Nicolas Vincent (2011) explores the implications of firms’ fear of customer anger and customers’ lack of product comparison for macroeconomic fluctuations. In Vincent’s model, it is assumed that comparing prices and characteristics of alternative brands is time-consuming for a consumer. While some consumers are bargain hunter whose opportunity costs from shopping is zero, most customers are loyal to a certain firm as long as posted prices are not raised. When consumers observe a price increase, they receive signal that a better alternative may be available, and thus they engage in search for alternatives. Unlike standard economic models, firms are free to adjust their nominal prices because they do not face any menu costs. However, they are aware of the fact that their pricing decisions will affect their future profits by affecting their customer base. This micro-founded mechanism generates price stickiness and is also coherent with frequently observed sales at the retail level.

Now let us discuss some price setting anomalies displayed by the firm. Consider a case where firms charge prices with lump sum components and a "per unit" component that is well below the marginal cost. As an illustrative example provided by Della Vigna and Malmandier (2006), many health clubs offer a plan with a monthly fee that allows buyers of the plan an unlimited number of visits. That is, the "per visit" fee equals zero. This is a puzzling phenomenon considering the fact that health clubs' marginal cost is not zero and that marginal cost rises with the number of visits.

One explanation for the above case that is provided by Della Vigna and Malmendier (2004) is that consumers are overconfident about their tendency to use certain services. Many consumers strongly believe that they will benefit disproportionately if services are priced at zero marginal price, even if they know that an average consumer generally does not benefit from such a price plan. Another plausible explanation is that people wish to avoid facing the tradeoff between paying a price and consuming. In other words, consumers avoid the recurrence of purchasing decisions by making a big one decision at the beginning. Survey evidence by Prelec and Loewenstein (1998) for a variety of services such as health club plans and foods during cruises, people tend to prefer to pay a fixed fee at the beginning than paying a fee per-use even if the total cost and usage are equal.

Another price setting anomaly that is encountered in our daily lives is the price that ends with a digit 9. Firms extensively charge a price with this ending because studies reveal that consumers are particularly attracted to purchasing products whose price ends with a 9. A study by Twedt (1965) and Levy et al (2007) reports that over half of the prices that they observe end in the digit 9. One explanation for this observation is that people tend to absorb price information from left to right and recall only the first few significant digits. Therefore, firms are less inclined to charge a price ending with a zero than a slightly lower price that ends with a 9.

An interesting observation by Levy et al. (2007) is that prices ending in 9 are less likely to be changed than prices ending in other digits. At the same time, if it does change, the typical magnitude of price change is larger for prices ending in 9. Therefore, it follows that prices with 9 endings are more sticky.

3 The Model

In this section, we present Rotember's (2005) behavioral price setting model. This model describes customer anger at price increases, and provides implications in the frequency of price adjustment. We first consider a one-period model with fairness concerns, and then move on to the multi-period general equilibrium model.

3.1 A One-Period Model with Fairness Concerns

A unit mass of households each produce his own differentiated product, and each household, which is denoted by i, obtains a utility at period t which is given by

$$w_t^i = u\left(C_t^i\right) - v(\phi_t^i y_t^i) \quad \text{where} \quad C_t^i = \left[\int_0^1 c_t^i(z)^{(\theta-1)/\theta} dz\right]^{\theta/(\theta-1)}. \tag{1}$$

Household's utility function u is concave and increasing while his cost function v is convex and increasing. A random variable indicating the cost of production is denoted by ϕ_t^i, the output of household i at period t is given by y_t^i, and the household's consumption of good z at period t is denoted as $c_t^i(z)$. Maximization of this utility implies that $C_t^i = E_t^i/P_t$, where E_t^i denotes household i's total expenditure on consumer goods. This implies that $c_t^i(j)$, which is the purchase of good j, equals $E_t^i(P_t^j/P_t)^{-\theta}$ where P_t^j is the price of good j that is charged by household j for its product, and P_t is the price index that equals

$$P_t = \left[\int_0^1 \left(P_t^i\right)^{1-\theta} di\right]^{1/(1-\theta)}. \tag{2}$$

Since $c_t^i(j) = (E_t^i/P_t)(P_t^i/P_t)^{-\theta}$, by market clearing condition $\int_0^1 c_t^j(i)\, dj = y_t^i$,

$$\begin{aligned} y_t^i &= \int_0^1 (E_t^i/P_t)(P_t^i/P_t)^{-\theta} dj \\ &= (P_t^i/P_t)^{-\theta} \int_0^1 (E_t^i/P_t) dj \\ &= (E_t/P_t)(P_t^i/P_t)^{-\theta} \end{aligned}$$

Thus, if all households maximize (1) and if producers sell the quantity that is demanded by households, y_t^i would equal $(E_t/P_t)(P_t^i/P_t)^{-\theta}$, where E_t is the total household expenditure at period *t.*

There is a threshold price level $\bar{P}_t^i$ such that consumers would stop buying the product despite the fact that their utility maximization leads to a positive amount of purchase at this price. From this kind of consumer behavior we can infer that consumers are actually maximizing a utility function that is more complicated than (1). This new type of utility function incorporates consumer's perception of whether firms are being altruistic towards them. In fact, consumers expect firm *i* to set a price such that maximizes

$$w_t^i + \lambda^i \int_{j \neq i} (w_t^j - w_{0t}^j), \tag{3}$$

where λ^i is a parameter that measures firm *i*'s altruism level while w_{0t}^j is household *j*'s base level utility that he gains when he does not consume any amount of good *i.* Note that when λ^i takes the value of zero, firm's maximization problem would be equal to a prototypical profit maximization problem in the absence of fairness considerations. However, firms keep λ^i above zero in the presence of fear for antagonizing their customers. The main difference of the behavioral pricing model from prototypical non-behavioral pricing model lies in this non-zero value of λ^i

For simplicity, assume that in the one period model, the producer spends all his earned revenue in consuming goods at period *t*, so that $E_t^i = P_t^i y_t^i$. Thus, since $C_t^i = E_t^i/P_t$, household's utility $w_t^i = u(C_t^i) - v(\phi_t^i y_t^i)$ can be represented as

$$w_t^i = u\left(P_t^i\left(\frac{E_t}{P_t}\right)\left(\frac{P_t^i}{P_t}\right)^{-\theta} / P_t\right) - v\left(\phi_t^i\left(\frac{E_t}{P_t}\right)\left(\frac{P_t^i}{P_t}\right)^{-\theta}\right) \tag{4}$$

Differentiating (4) with respect to P_t^i yields,

$$\begin{aligned} &u'(C_t^i)(1-\theta)\left(\frac{E_t}{P_t}\right)\left(\frac{P_t^i}{P_t}\right)^{-\theta}\frac{1}{P_t} - v'\phi_t^i\left(\frac{E_t}{P_t}\right)(-\theta)\left(\frac{P_t^i}{P_t}\right)^{-\theta-1}\frac{1}{P_t} \\ &= (1-\theta)\ \frac{E_t}{P_t}\frac{u'\left(C_t^i\right)}{P_t}\left(\frac{P_t^i}{P_t}\right)^{-\theta} + \theta\frac{E_t}{P_t}\frac{\phi_t^i v'}{P_t}\left(\frac{P_t^i}{P_t}\right)^{-\theta-1} \end{aligned}$$

Thus, the maximization of the producer's utility function leads to a price satisfying

$$(1-\theta)\frac{E_t}{P_t}\frac{u'\left(C_t^i\right)}{P_t}\left(\frac{P_t^i}{P_t}\right)^{-\theta} + \theta\frac{E_t}{P_t}\frac{\phi_t^i v'}{P_t}\left(\frac{P_t^i}{P_t}\right)^{-\theta-1} - \lambda\int_{j\neq i}\frac{E_t^j}{P_t}\frac{u'\left(C_t^j\right)}{P_t}\left(\frac{P_t^i}{P_t}\right)^{-\theta} = 0. \tag{5}$$

In a symmetric equilibrium where all households have identical marginal utilities, the optimal price satisfies

$$\frac{P_t^i}{P_t} = \frac{\theta\phi_t^i}{\theta+\lambda-1}\frac{v'}{u'}\ . \tag{6}$$

Moreover, differentiating P_t^i with respect to λ, we get

$$\begin{aligned} \frac{\partial P_t^i}{\partial\lambda} &= \theta\phi_t^i(-1)(\theta+\lambda-1)^{-2}v'(u')^{-1}P_t \\ &= P_t\frac{-\theta\phi_t^i v'}{(\theta+\lambda-1)^2 u'} < 0 \end{aligned}$$

and differentiating P_t^i with respect to ϕ_t^i we get

$$\frac{\partial P_t^i}{\partial \phi_t^i} = \theta(\theta + \lambda - 1)^{-1} v'(u')^{-1} P_t$$

$$= P_t \, \frac{\theta v'}{(\theta+\lambda-1)u'} > 0 \, .$$

Thus a higher value of the altruism parameter, λ, leads to a lower P_t^i, whereas higher cost, ϕ_t^i leads to a higher P_t^i.

Consumers are unaware of the producers' costs or levels of altruism parameters. Therefore, by using the information available to them, consumers test whether they can reject the null hypothesis that the altruism parameter of the producer is at least equal to $\bar{\lambda}$, the minimal level of altruism expected from the producer. If consumers can reject this hypothesis, consumers will stop purchasing goods from this producer. Therefore, household j determines his consumption by maximizing

$$u(C_t^i) - \int_{i \neq j} \lambda_c \, \psi(\hat{\lambda}_i)(w_t^i - \bar{w}_t^i), \tag{7}$$

where $\bar{w}_t^i$ is the baseline value of w_t^i when consumers do not make any purchases, λ_c is an arbitrarily large number, and ψ is a function that takes the value of zero if customers cannot reject the hypothesis that λ is at least $\bar{\lambda}$. Alternatively, if consumers are able to reject the hypothesis that $\lambda^i = \bar{\lambda}$, the step function ψ takes the value of 1. The actual hypothesis that the consumers are testing is the hypothesis that the firm's marginal cost that is implied by equation (6) with $\lambda = \bar{\lambda}$ is consistent with the consumers' subjective distribution concerning these costs. This hypothesis would be rejected if the price set by the producer is above the critical level $\bar{P}_t^i$, because this would suggest that the producers' costs are implausibly large.

Let G be the p.d.f. over the critical value $\bar{P}_t^i$ that the producers have. If the firm knows the true value of $\bar{P}_t^i$, this p.d.f. would take the form of a step function. Supposing that producers are selfish, P_t^i maximizes

$$[1 - G(P_t^i)]\left[u\left(\frac{E_t}{P_t}\left(\frac{P_t^i}{P_t}\right)^{1-\theta}\right) - v\left(\phi_t^i \frac{E_t}{P_t}\left(\frac{P_t^i}{P_t}\right)^{-\theta}\right)\right] \tag{8}$$

and the corresponding first order condition is

$$\begin{aligned}[1 - G(P_t^i)]\frac{E_t}{P_t}\left(\frac{P_t^i}{P_t}\right)^{-\theta-1}&\left\{(1-\theta)u'\frac{P_t^i}{P_t} + \theta\phi_t^i v'\right\} \\ -g(P)&\left[u\left(\frac{E_t}{P_t}\left(\frac{P_t^i}{P_t}\right)^{1-\theta}\right) - v\left(\phi_t^i \frac{E_t}{P_t}\left(\frac{P_t^i}{P_t}\right)^{-\theta}\right)\right] \leq 0.\end{aligned} \tag{9}$$

The solution to this first order condition is to set $P_t^i = P^*$ if $G(P^*) = 0$ for the price P^* that makes $(1-\theta)u'\frac{P_t^i}{P_t} + \theta\phi_t^i v'$ equal zero. Otherwise, the optimal price would be lower than P^*. In this case, there are two subcases to consider. In the first case, the price P_t^i maximizing (8) is interior, and thus at this price equation (9) is satisfied as an equality. In the second case, the price P_t^i that maximizes equation (8) is the price $\tilde{P}$ that satisfies $G(\tilde{P}) = 0$, which therefore guarantees that consumers regard this price as fair.

If the optimal price P^* satisfies the first order condition (9) because $G(P^*) = 0$, the firm is able to choose its first best action. If instead $G(P^*)$ were greater than zero, and if the price that maximizes (8) is lower than its price in the previous period, the firm would keep its price equal to P_{t-1}. Keeping the price equal to its previous level allows the firm to maintain a price that is closer to its unconstrained optimum without generating the possibility of antagonizing customers.

If instead, the price that maximizes (8) is $\tilde{P}$ such that makes $G(\tilde{P})$ equal zero, the prices would be expected to rise because by doing so, the firm is able to increase the value of its objective function without creating the risk of consumer complaints. Now suppose that the optimum is interior and the price that satisfies the first order condition (9) is very close to P_{t-1}. If this is the case, it is better for the firm to keep its prices constant because the firm gets $u(P_{t-1}) - v(P_{t-1})$ by keeping prices constant, whereas he will get $[1 - G(P_t^i)[u(P_{t-1}) - v(P_{t-1})]$ if he raises the price to P_t^i. Since $G(P_t^i)$ is greater than zero, and since P_{t-1} and P_t^i are sufficiently close, $[1 - G(P_t^i)[u(P_{t-1}) - v(P_{t-1})]$ might be less than $u(P_{t-1}) - v(P_{t-1})$. Hence, the prices would stay rigid in the sense of staying constant.

Producers' fear of antagonizing customers works as a fixed cost of changing prices, and this cost makes producers to keep their prices constant. The difference of this model from the one with simple fixed costs, is that not only the price change par se, but also the size of the price change matters as well. According to Zbaracki et al (2004), salesmen are more worried about customers' retaliation for large price increases than for small price increases. If customers have diffuse priors about the level of costs, but are precisely informed about the marginal changes in costs between two consecutive periods, they are more likely to react negatively to large price changes. Therefore, price increases than are not accompanied by corresponding increases in costs are highly likely to trigger customer anger. If we assume that customers assess firm's fairness only when the firm changes its prices, and if the optimal price at period t, P_t^i, is interior and is close to the price level in the previous period, firm is more likely to keep its prices constant.

3.2 A Multi-Period General Equilibrium Model

In this section, above presented model is extended to a dynamic setting. Suppose, that in the absence of fairness concerns, that household *i's* utility function at period t is given by

$$E_0 \sum_{t=0}^{\infty} \beta^t w_t^i. \tag{10}$$

Each individual consumes a fixed fraction E_t/P_t at period t, which implies that the equilibrium value of the marginal utility, u', is equal across ex ante identical households. Also, let us suppose that households are able to borrow and lend at a riskless nominal rate R_t. Therefore, households are indifferent between consuming an additional unit of consumption in one period and expecting to consume $(1 + R_t)P_t/P_{t+1}$ additional units of consumption in the next period. Putting this into an equation yields

$$E_t\left\{\frac{\beta(1+R_t)P_t u^{'}(Y_{t+1})}{P_{t+1}}\right\} = u'(Y_t). \quad (11)$$

Despite the fact that all firms are identical in our setting, consumers' beliefs about what constitutes fair pricing for any given firm evolves stochastically from period to period. It is believed by consumers that the cost ϕ_t^i of any given firm takes the value of either Φ_t^H or Φ_t^L, where $\phi_t^i = \Phi_t^L < \Phi_t^H$. Moreover, consumers independently draw signals equal to $\hat{\phi}_t^i$ from the p.d.f. $F_t(\hat{\phi})$, for each firm. It is viewed by the households that these signals are in fact equal to ϕ_t^i plus a random measurement error z which is drawn from the p.d.f $H(z)$. Therefore, when customer receives a signal less or equal to $\hat{\phi}_t^i$, the consumers' subjective probability that the true value of the cost is Φ_t^H equals $H(\hat{\phi}_t^i - \Phi_t^H)$.

In a multi-period model, firms do not ever find it optimal to decrease their prices when the steady state level of inflation is sufficiently high. Therefore, consumer reactions to price decreases may be unimportant.

Consumers determine whether the new price P_t^i set by the firm is consistent with $\lambda \geq \bar{\lambda}$ for each of the two possible values of cost by using equation (6), which we re-state here for convenience:

$$\frac{P_t^i}{P_t} = \frac{\theta\phi_t^i}{\theta+\lambda-1}\frac{v'}{u'}\,.$$

If the true cost of the firm is Φ_t^H, a firm can raise its price without triggering consumer anger as long as

$$P_t^i \leq P_t\frac{\theta\phi_t^i}{\theta+\bar{\lambda}-1}\frac{v^{'}}{u^{'}}\,. \quad (12)$$

Suppose that the firm changes its price but keeps its below the bound presented in equation (12). Given a signal as ϕ_t^i, since consumers' subjective probability that the firm's true cost is Φ_t^H equals $H(\hat{\phi}_t^i - \Phi_t^H)$, consumers will reject the hypothesis that the firm's altruism parameter is at least equal to $\bar{\lambda}$ if

$$H(\hat{\phi}_t^i - \Phi_t^H) \leq \gamma, \tag{13}$$

where γ is the size of the test. Firms would be better off to maintain their prices from the previous period if their $\hat{\phi}_t^i$ is lower than the critical value of this test.

Assuming that firms know the value of the cost that consumers receive as signals, the probability that they keep their prices constant would be α_t, which is given by

$$\alpha_t = F_t(H^{-1}(\gamma) + \Phi_t^H). \tag{14}$$

If we let F_t and Φ_t^H to be constant over time, this model would be similar to the Calvo (1983) model.

In the Calvo model, the probability of changing prices, α, is fixed. The probability of changing prices, in contrast, is variable in our behavioral model and is a function of the signal $\hat{\phi}_t^i$. In our model, when customers realize that a specific firm's cost is below some critical level, they stop purchasing products from this firm. However, in the presence of random measurement error, customers may not be able to determine clearly whether a firm's pricing is fair

Let us now suppose that producers can set price to any level whenever the condition in (13) is violated. Given full insurance markets, a dollar increase in profits in period $t+j$ increases expected utility of period t by $E_t\beta^j u'(Y_{t+j})/P_{t+j}$. Therefore, the optimal price would maximize

$$E_t \sum_{j=0}^{\infty} \beta^j \left(\prod_{l=1}^{j} \alpha_{t+l}\right) \left[u'(Y_{t+j}) Y_{t+j} \left(\frac{P_t^i}{P_{t+j}}\right)^{1-\theta} - v\left(Y_{t+j}\left(\frac{P_t^i}{P_{t+j}}\right)^{-\theta}\right)\right] \tag{15}$$

over P_t^i. Notice that since α is fixed in the Calvo model, a firm would maximize

$$E_t \sum_{j=0}^{\infty} (\beta\alpha)^j \left[u'(Y_{t+j}) Y_{t+j} \left(\frac{P_t^i}{P_{t+j}}\right)^{1-\theta} - v\left(Y_{t+j}\left(\frac{P_t^i}{P_{t+j}}\right)^{-\theta}\right)\right]$$

as opposed to equation (15).

The first order condition derived from (15) is

$$E_t \sum_{j=0}^{\infty} \beta^j \left(\prod_{l=1}^{j} \alpha_{t+l}\right) Y_{t+j} \left(\frac{P_t^i}{P_{t+j}}\right)^{-\theta} \left[(1-\theta) u'(Y_{t+j}) \frac{P_t^i}{P_{t+j}} \right.$$
$$\left. -\theta v'\left(Y_{t+j}\left(\frac{P_t^i}{P_{t+j}}\right)^{-\theta}\right)\right] = 0.$$

Suppose that $u'(c) = u_0 c^{-\sigma}$ and $v'(y)$ is proportional to $v_0 y^{\omega}$. Let X_t be P_t^i/P_t, and dividing it by $(P_t^i/P_t)^{-\theta}$ we obtain

$$X_t^{1+\theta\omega} = \frac{\theta v_0/u_0}{1-\theta} \frac{E_t \sum_{j=0}^{\infty} \beta^j (\prod_{l=1}^{j} \alpha_{t+l} (1+\pi_{t+l})^{\theta(1+\omega)}) Y_{t+j}^{1+\omega}}{E_t \sum_{j=0}^{\infty} \beta^j (\prod_{l=1}^{j} \alpha_{t+l} (1+\pi_{t+l})^{\theta-1}) Y_{t+j}^{1-\sigma}}, \tag{16}$$

where π_t denotes the inflation rate. The value of X_t will satisfy the condition (12) for sufficiently large values of Φ_t^H. Therefore, firms whose costs are sufficiently large will change their prices according to equation (16).

Since

$$P_t = \left[\int_0^1 (P_t^i)^{1-\theta}\, di\right]^{1/(1-\theta)} \quad \text{implies} \quad \left[\int_0^1 \left(\frac{P_t^i}{P_t}\right)^{1-\theta} di\right]^{1/(1-\theta)} = 1,$$

given the common choice of P_t^i/P_t,

$$\left[(1-\alpha_t)X_t^{1-\theta} + \alpha_t\left(\frac{P_{t-1}}{P_t}\right)^{1-\theta}\right]^{1/(1-\theta)} = 1. \tag{17}$$

Equation (17) simply states that a fraction α_t of firms keep their prices constant by maintaining their price from the previous period, whereas a fraction$(1-\alpha_t)$ of firms change their prices to P_t^i. In a steady state where inflation and the probability of changing prices are constant, this implies that

$$(1-\alpha)X^{1-\theta} + \alpha(1+\pi)^{\theta-1} = 1. \tag{18}$$

By differentiating equation (17), and using (18) to substitute for the steady state value of X, we can obtain

$$\tilde{\pi}_t = \frac{1-\alpha(1+\pi)^{\theta-1}}{\alpha(1+\pi)^{\theta-1}}\,\tilde{x}_t + \frac{(1+\pi)^{1-\theta}-1}{(1-\alpha)(\theta-1)}\,\tilde{\alpha}_t, \tag{19}$$

where $\tilde{x}_t, \tilde{\alpha}_t,$ and $\tilde{\pi}_t$ denote the logarithmic deviations from steady state values of X, α, and π, respectively.

Differentiating equation (16) and using L to denote the lag operator,

$$(1+\theta\omega)\tilde{x}_t = E_t \frac{1}{1-\lambda_1/L}\left(c_1^y \tilde{y}_t + \lambda_1 \tilde{\alpha}_{t+1} + \lambda_1 \theta(1+\omega)\tilde{\pi}_{t+1}\right)$$
$$+E_t \frac{1}{1-\lambda_2/L}\left(c_2^y \tilde{y}_t - \lambda_2 \tilde{\alpha}_{t+1} - \lambda_2(\theta-1)\tilde{\pi}_{t+1}\right),$$

$$\lambda_1 \equiv \alpha\beta(1+\pi)^{\theta(1+\omega)}, \quad \lambda_2 \equiv \alpha\beta(1+\pi)^{\theta-1}, \quad c_1^y \equiv (1+\omega)(1-\lambda_1),$$
$$c_2^y \equiv (\sigma-1)(1-\lambda_2), \tag{20}$$

where $\tilde{y}_t$ denotes the logarithmic deviation from Y.

The coefficient of $\tilde{\alpha}$ in equation (19) becomes zero when the steady state rate of inflation equals zero. Furthermore, the coefficient of $\tilde{\alpha}$ for equation (20) also becomes zero since λ_1 and λ_2 cancel each other out. Therefore, when the steady state rate of inflation equals zero, small variations in α do not have effects on the economy. When π takes the value of zero, the steady state value of X equals 1.00, which implies that average price change of each firm equals zero. Thus, despite an increase in the number of firms changing their prices, the price level is generally not affected. When the steady state rate of inflation is positive, however, X is greater than 1. In this case, the typical price changer will increase his price, and therefore even a small variation in α will affect the price level.

Furthermore, suppose that the linearized reaction function for the central bank is given as

$$\tilde{\imath}_t = c_\pi^i \tilde{\pi}_t + c_1^i \tilde{\imath}_{t-1} + \varepsilon_t^i. \tag{21}$$

Also, suppose that $\tilde{\alpha}_t$ is given by

$$\tilde{\alpha}_t = c_X^\alpha \tilde{x}_t + c_\pi^\alpha \tilde{\pi}_{t-1}, \tag{22}$$

where the parameter value of c_X^α is positive whereas that of c_π^α is negative.

In the following section, we provide empirical results to analyze how the economy responses to various shocks.

4 Empirical Results

4.1 Responses of the economy to the shock

In this section we analyze the response of the economy to mark-up shocks ε_t^π, demand shocks ε_t^y, and monetary policy shocks ε_t^i. Parameter values from the literature are used. Just as in Rotemberg and Woodford (1997), the discount factor β is set to .99, σ is set to 1, θ is set to 7.88, and ω equals .47.

While our analysis mainly focuses on the case where the steady state rate of inflation is 5 percent, we also analyze the case with the steady state rate ofinflation of 0% for comparison. Suppose that $\alpha = .76$ and that the two parameters of the monetary policy rule, c_π^i and c_1^i take the value of .9. These high values for the parameters of the monetary policy rule ensure that monetary policy shock has persistent effects and also that the equilibrium is determinate. The parameter values of c_X^α and c_π^α are set to 2.5 and -15, respectively.

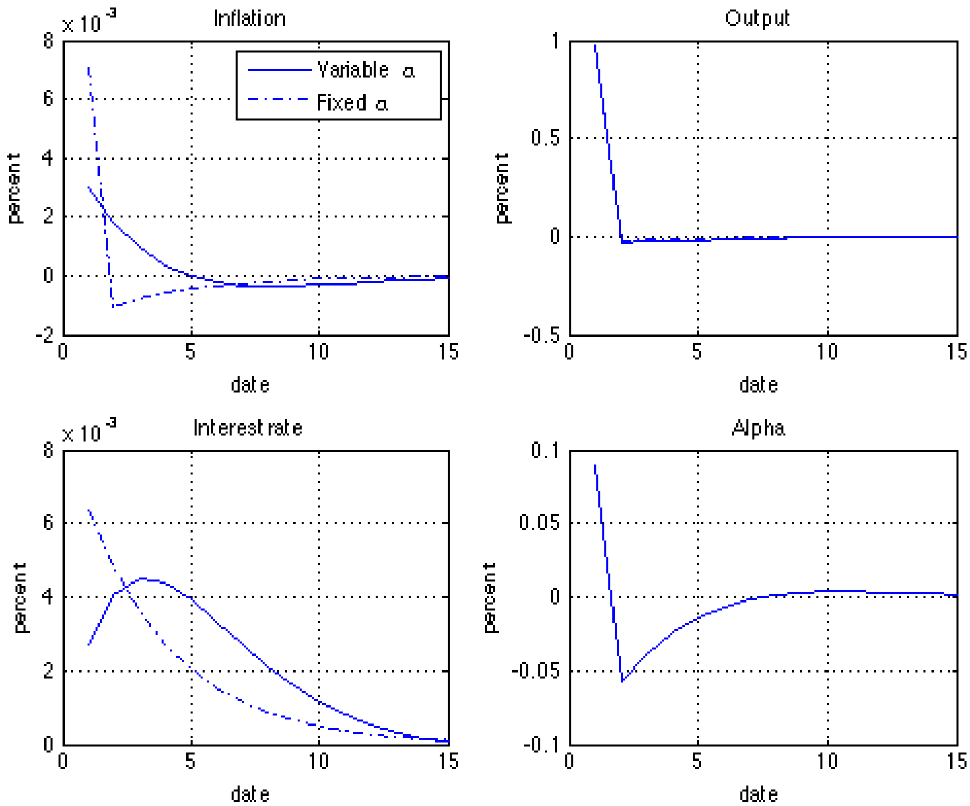


figure 2: Orthogonalized Shock to ε_y for both constant and variable alpha when steady state rate of inflation is 5 percent

4.1.1 Responses to Demand Shocks

Figure 2 illustrates responses of macroeconomic variables to demand shock when annual steady state inflation rate is given by 5 percent. Responses of variables for both constant and variable α are illustrated for comparison.

It is clear that the direction of response for inflation, output and interest rate is equivalent regardless of whether α is variable or fixed: inflation, outcome and interest rate decreases as a response to a demand shock. Figure 2 also reports responses of $\tilde{\alpha}$ when $\tilde{\alpha}$ is given by

$$\tilde{\alpha} = c_X^{\alpha}\tilde{x}_t + c_{\pi}^{\alpha}\tilde{\pi}_{t-1}$$

where $c_X^{\alpha} = 2.5$ and $c_{\pi}^{\alpha} = -15$. These parameters are such that make α_t to initially fall and then to rise.

One interesting observation is that the interest rate displays a hump-shaped response when α is variable whereas it always displays a negative slope in the case of a fixed α. When α is fixed, the largest increase (although the absolute amount is trivial) in interest rate takes place in the immediate aftermath of the demand shock, where it increases by .006 percent. When α is variable, however, interest rate rises by approximately .003 percent, and it continues to increase until it reaches its peak after roughly 3 quarters.

4.1.2 Responses to the Monetary Policy

Figure 3 illustrates responses of macroeconomic variables to a monetary shock when annual steady state inflation rate is 5 percent. Output reduces by 4

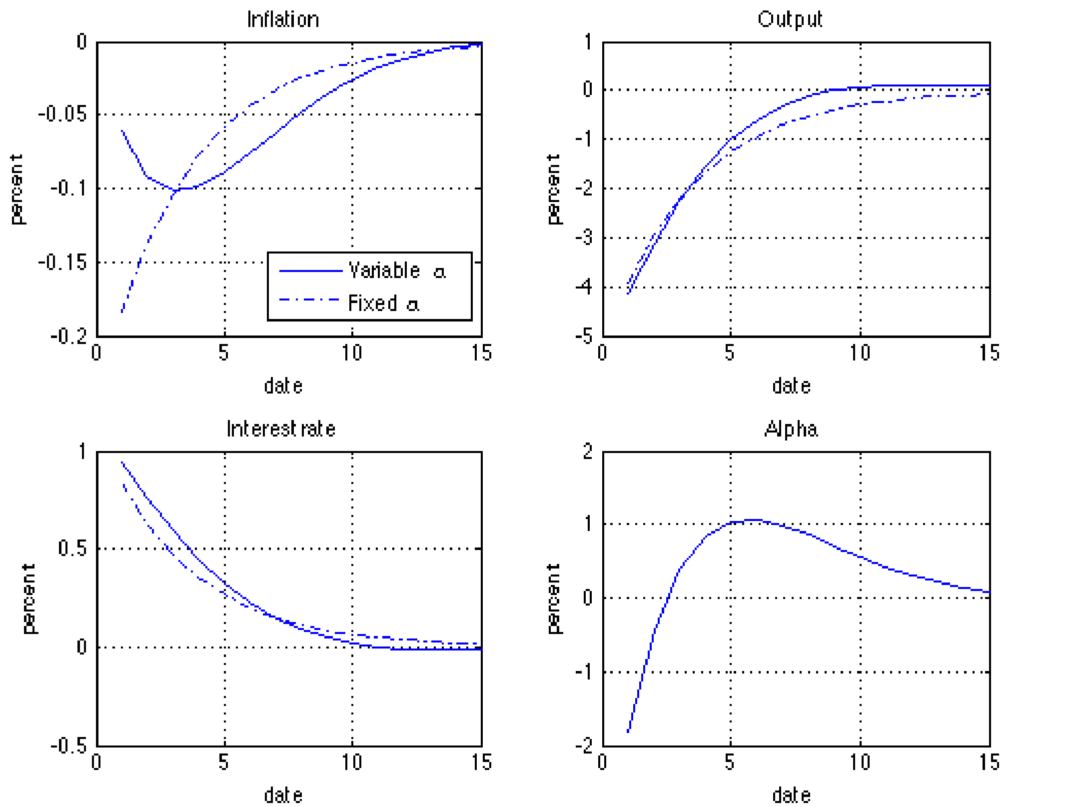


figure 3: Orthogonalized Shock to ε_i for both constant and variable alpha when steady state rate of inflation is 5 percent

percent immediately after the shock for both fixed and variable α, and it reaches its steady state in roughly 10 quarters. Similarly, a monetary shock leads to an increase in interest rate by approximately 1 percent regardless of whether α is fixed or variable, and it reaches its steady state in 10 quarters. A noteworthy observation is that when α is constant, the drop in inflation is largest in the quarter where monetary shock first hits the economy. The response of the inflation when α is variable, however, differs in the sense that the largest reduction in inflation does not occur immediately after the shock. As can be seen from figure 3, the largest drop in inflation when α is variable takes place after 2 quarters. In Rotemberg and Woodford (1997), the largest response in inflation happens after two quarters, whereas Christiano et al (2005) report a longer delay with a maximum response after 9 quarters. By close observation, we can see that the fall in inflation is much smaller in the initial quarter than in the case where α is fixed. Inflation exhibits a fall by approximately .18 percent with an initial increase in the rate of interest of .88 percent when α is fixed. When α is variable, in contrast, inflation initially decreases by only .06 percent despite a .95 percent rise in interest rate. It is quite surprising to see that neither the response of output nor that of interest rates is significantly affected by these altered dynamics of inflation.

4.1.3 Responses to Mark-up Shocks

Figure 4 reports the responses of macroeconomic variables to a mark up shock when annual steady state inflation rate is given by 5 percent. With a mark up shock, the inflation reports an initial increase of .06 percent for both constant and variable α. For fixed α, after an initial increase, inflation displays a rapid decline below it's steady state by rougly .01 percent. Inflation displays a

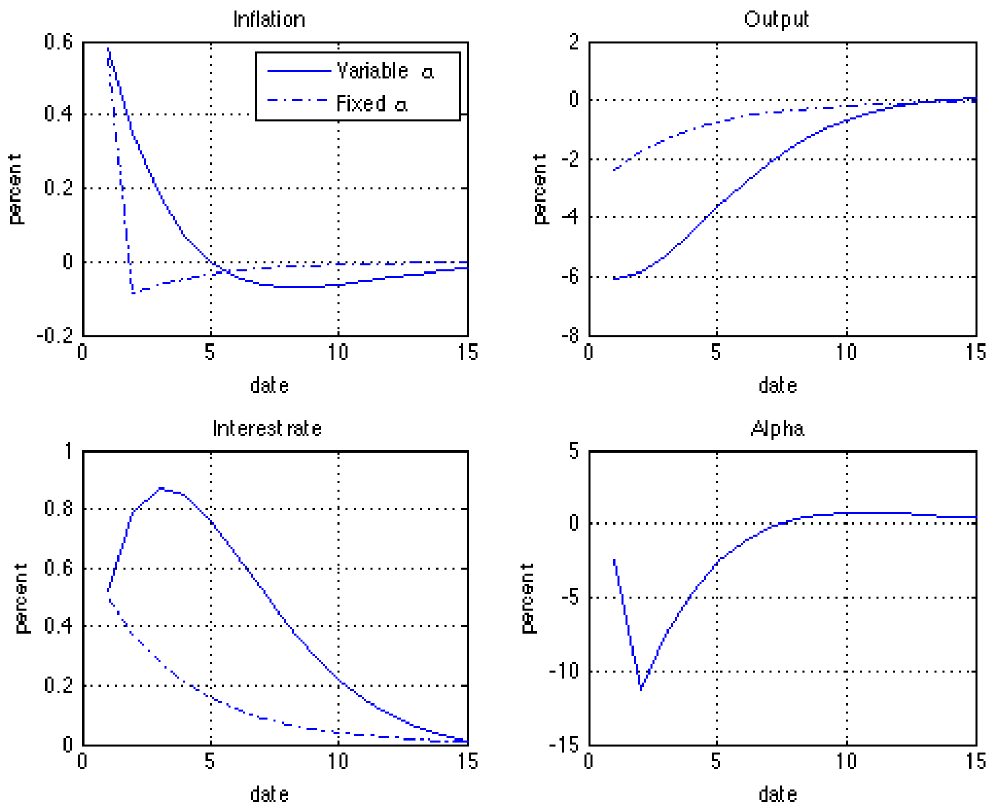


figure 4: Orthogonalized Shock to ε_π for both constant and variable alpha when steady state rate of inflation is 5 percent

similar path for variable α. The only different is that the fall in inflation is much more slow and gradual when α is variable. The initial decrease in output is much larger when α is variable. In the latter case, output decreases by 6 percent whereas it exhibits a decrease of 2 percent when α is fixed. Thus, the response path of output is much steeper when α is variable.

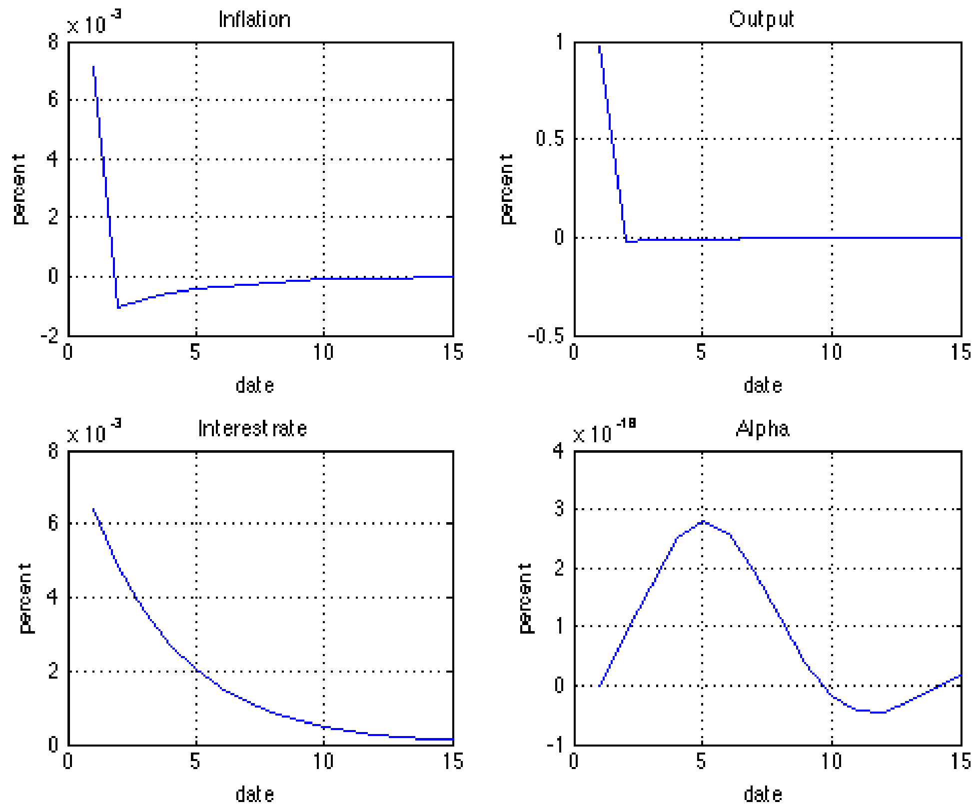


figure 5: Orthogonalized shock to ε_y (Responses with exogenous alpha)

When inflation increases by approximately .6 percent, interest rate increases by approximately .5 percent. Once again, we are able to observe a hump shaped response of the interest rate when α is variable. When α is fixed, the largest increase in interest rate takes place in the immediately after the inflation shock. When α is variable, in contrast, the largest increase in interest rate occurs approximately 3 quarters after the shock. For a relatively modest difference in inflation for constant and variable α's after 3 quarters, interest rate for variable α and fixed α display a gap of approximately .7 percent.

We next consider the case where α is given exogenously. Suppose that the exogenous response of α_t is given by the following pattern:

$$\tilde{a}_t = 1.02\tilde{a}_{t-1} - .116\tilde{a}_{t-2} - .302\tilde{a}_{t-3} - c^{\varepsilon}\varepsilon_t^i.$$

With c^{ε} set equal to 3, figure 5, figure 6, and figure 7 report the resulting responses of output, inflation and interest rates. The responses of output, inflation and interest rates to demand and mark up shocks do not vary whether α is fixed or variable. Thus the responses created by these variables demonstrate exactly the same path as that in the case where α is fixed. The only variation between responses when α is fixed and variable can be observed by the impulse response to monetary shocks. Another thing to note is the response pattern of α: immediately after the contraction, α drops by a large amount, then rises above its steady state value.

Figure 6 depicts the responses of inflation, output, and interest rates to monetary shock when α is determined exogenously, and when the steady state inflation rate is given by 5 percent. In the immediate aftermath of monetary contraction, α drops by approximately 3 percent, and then rises after a few quarters. Since α denotes the probability that firms keep their prices constant, this observation implies that the fraction of price adjusters rises as a result of monetary contraction, but that this fraction falls below its steady state after a few quarters. By observing the response of the inflation, we can clearly see that the response of inflation in delayed for several quarters because the largest drop in inflation takes place after approximately 7 quarters.

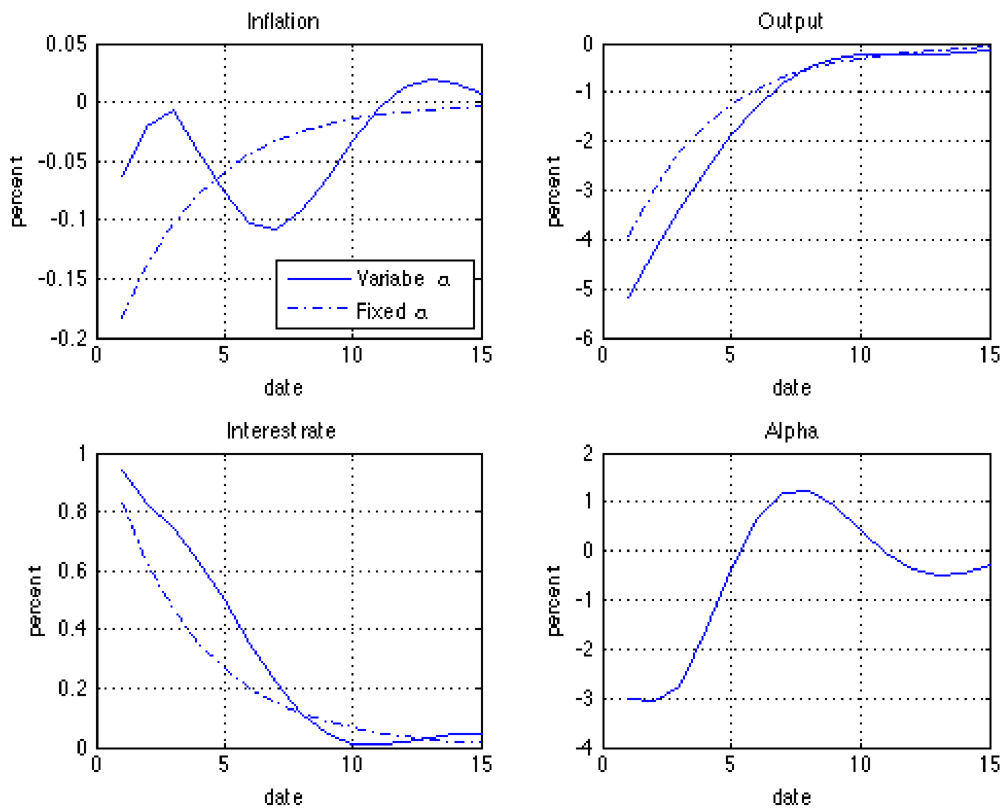


figure 6: Orthogonalized Shock to ε_i (Responses with exogenous alpha)

This response of inflation justifies the pattern that α takes, namely the initial rush of price adjustments and the subsequent reduction in the fraction of price adjusting firms. This initial sudden increase in price adjustments could be attributed to the reduction in

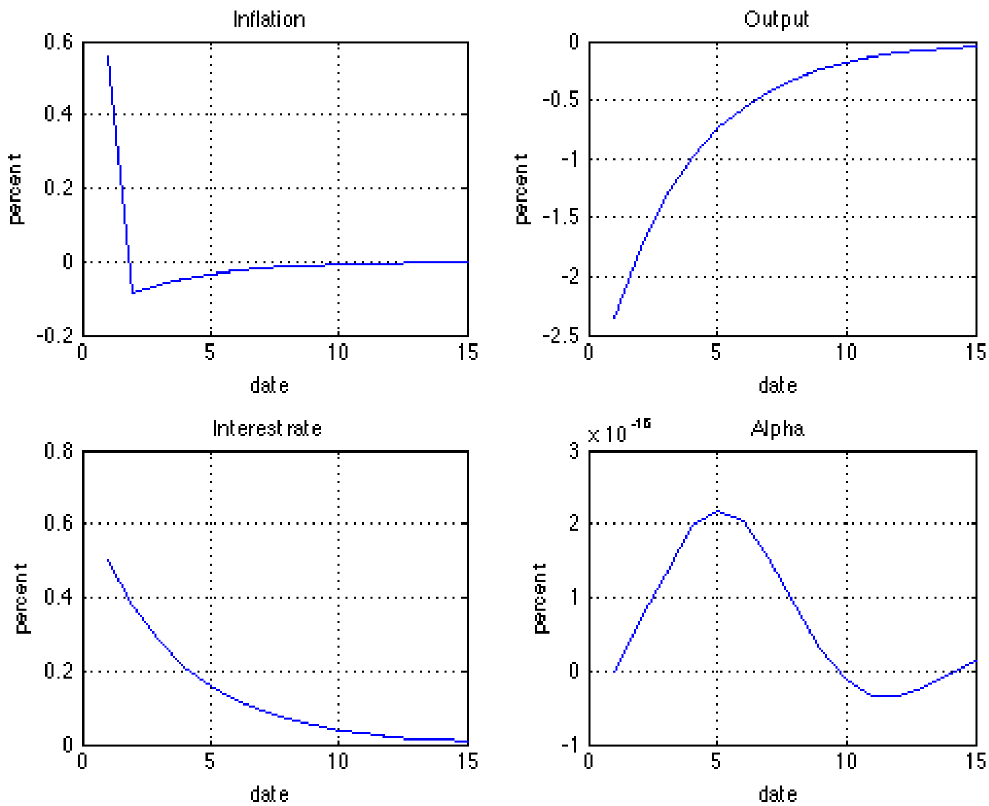


figure 7: Orthogonalized Shock to ε_π (Responses with exogenous alpha)

X_t caused by the contractionary policy. It could also be attributed to a firm's desire to raise prices while they can still point to a recent relatively high inflation as their justification for price adjustment. Thus the responses of α given in the above equation generated a pattern of inflation responses that make the responses of price adjustment assumed by the equation possible.

4.2 Parameter Estimates

In this section, we present parameter estimation results of the behavioral model obtained with Bayesian estimation techniques using three key macroeconomic quarterly US time series data over the period 1947:1 – 2004:4 as observable variables: the log difference of real GDP, the log difference of the GDP deflator, and federal funds rate. Output is defined as LN((GDPC96/LNSindex)*100, where GDPC96 is the Real Gross Domestic Product and LNSindex is the Labor Force Status index, ages 16 and older. Inflation is defined as LN(GDPDEF/GDPDEF(-1))*100, where GDPDEF is Gross Domestic Product - implicit price deflator. Interest rate is defined as (Federal Funds Rate)/4. All data are obtained from U.S. Department of Commerce, Bureau of Economic Analysis.

4.2.1 Prior Distribution of the Parameters

In order to calculate the likelihood function of the observed data series, Kalman filter is used. This likelihood function needs to be combined with prior information for the model parameters in order to obtain the posterior distribution of the parameters. Table 1 gives an overview of our assumptions regarding the prior distributions of the estimated parameters. All the variances of the shocks are assumed to follow an Inverted Gamma distribution. Inverted Gamma distribution guarantees a positive variance with a rather large domain.

TABLE 1 – PRIOR DISTRIBUTIONS FOR DSGE MODEL PRAMETERS

Parameters	Prior Mean	Mode	Standard Deviation	t-statistic	Prior	Prior St.Deviation
σ	1.050	1.0957	0.0145	75.6857	Gamma	0.0250
θ	7.830	7.8217	0.0148	527.5945	Gamma	0.0350
c_π^i	0.920	0.7928	0.0042	187.3882	Normal	0.0200
c_1^i	0.880	0.7210	0.0030	244.3635	Normal	0.0250
ω	0.440	0.4231	0.0212	19.9171	Gamma	0.0450
α	0.780	0.6963	0.0080	86.6216	Beta	0.0230
β	0.970	0.9652	0.0188	51.2835	Beta	0.0213
π	0.052	0.0181	0.0010	18.2484	Normal	0.0360
c_X^α	2.530	2.5217	0.0276	91.4604	Gamma	0.0323
c_π^α	-14.970	-14.9695	0.0141	1063.2163	Normal	0.0315
ρ_π	0.600	0.5821	0.1230	4.7339	Beta	0.1000
ε_y	0.250	8.0966	0.4040	20.0424	Inv. Gamma	2.0000
ε_i	1.000	0.5628	0.0277	20.3149	Inv. Gamma	8.0000
ε_π	1.000	0.8558	0.0881	9.7141	Inv. Gamma	8.0000

The parameters describing the monetary policy rule, c_π^i and c_1^i, are described by a Normal distribution with mean 0.920 and 0.880 and standard errors 0.0200 and 0.0250, respectively. The fraction of firms keeping their prices constant, α, has a Beta distribution and fluctuates around 0.780 with a standard error of 0.0230. Parameters describing $\tilde{\alpha}_t$, namely, c_X^α and c_π^α, follow Gamma and Normal distributions, respectively, with mean 2.530 and -14.970 and standard errors 0.0323 and 0.0315, respectively. The discount factor, β, is described by a

4.1.2. Posterior Estimates of the Parameters

TABLE 2 – PARAMETER ESTIMATION RESULTS

Parameters	Prior Mean	Posterior Mean	Confidence	Interval	Prior	Prior St.Deviation
σ	1.050	1.1011	1.0568	1.1419	Gamma	0.0250
θ	7.830	7.8343	7.7807	7.8859	Gamma	0.0350
c_π^i	0.920	0.8009	0.7928	0.8112	Normal	0.0200
c_1^i	0.880	0.7242	0.7210	0.7283	Normal	0.0250
ω	0.440	0.4254	0.3516	0.4989	Gamma	0.0450
α	0.780	0.6869	0.6532	0.7312	Beta	0.0230
β	0.970	0.9524	0.9119	0.9932	Beta	0.0213
π	0.052	0.0191	0.0150	0.0224	Normal	0.0360
c_X^α	2.530	2.5142	2.4651	2.5660	Gamma	0.0323
c_π^α	-14.970	-14.9685	-15.0165	-14.9203	Normal	0.0315
ρ_π	0.600	0.5671	0.4078	0.7185	Beta	0.1000
ε_y	0.250	8.0725	7.3634	8.7267	Inv. Gamma	2.0000
ε_i	1.000	0.5756	0.5316	0.6230	Inv. Gamma	8.0000
ε_π	1.000	0.8662	0.7468	0.9809	Inv. Gamma	8.0000

Note: The posterior distribution is obtained using the Metropolis-Hastings algorithm

Beta distribution with a prior mean of 0.970 and prior standard deviation 0.0213. The prior mean of the steady state inflation rate is Normally distributed with a mean 0.052 and standard error 0.0360.

The rest of the parameters are assumed to be distributed as follows: σ is set around 1.050 with a standard error of 0.0250, θ is assumed to fluctuate around 7.830 with a standard error of 0.0350, and ω is set at 0.440 with a standard error of 0.0450. The prior distribution of ρ_π follows Beta distribution with a mean 0.600 and standard error 0.1000.

Table 2 summarizes the estimation results of the posterior distribution of the parameters from the behavioral pricing model, obtained by the Metropolis-Hastings algorithm. It gives the prior mean, posterior mean, 5 and 95 percentiles of the posterior distribution of the parameters. A sample of 50,000 draws was created, where the first 10,000 draws were neglected.

The posterior means of the parameters of the monetary policy rule, c_π^i and c_1^i, appear to be smaller than the values given from the previous literature. Whereas the prior mean of c_π^i is 0.920, the posterior mean equals 0.8009, and while the prior mean of c_1^i equals 0.880, its posterior mean equals 0.7242. Recall that in c_π^i and c_1^i were both equal to 0.9 in Rotemberg (2005). These rather high values for the parameters were given to ensure both that the monetary policy shock has persistent effects and that the equilibrium is determinate. However, we can observe from estimated results that c_π^i and c_1^i are in fact smaller. Thus it turns out that smaller values for the parameters of the monetary policy rule can also allow the effect of the monetary policy shock to be persistent.

The estimation result of the probability of keeping prices constant, α, is also noteworthy. The prior mean of α is 0.780 whereas the posterior mean equals 0.6869. Departure of the reset price from the average price, (i.e. X) is larger when inflation is larger. Therefore, it is assumed in Rotemberg (2005) that when the annual steady state rate of inflation equals 5 percent, a typical price changing firm charges a price 5 percent above that the average price so that the steady state value of X takes the value of 1.05. The typical price changing firm is then raising its price by P_t^i/P_{t-1}, or $X(1+\pi)$, which equals 6.3 percent. Using equation (18), this value of X implies that firms change their prices approximately once a year and the probability of changing price equals .76.

According to our estimation results, however, the value of the posterior mean of α equals 0.6869. This is because our estimated posterior mean values for θ and π are 7.8343 and 0.0191, respectively. Therefore, when the steady state value of X is 1.05, a typical price changer will raise his price by approximately 7 percent. Comparing the results of the Bayesian estimation with the results given in the literature provides interesting insights. The price increase rate is larger, and furthermore, the probability of keeping prices constant is lower in the estimated result. Thus, from what the estimation results reveal, a higher fraction of firms change their prices, and the magnitude of price increase is higher than the amount reported by previous studies.

Posterior mean of demand, monetary, and mark-up shocks are clearly different from those of the prior mean. The prior mean of the demand shock ε_y is 0.250 whereas the posterior mean is 8.0725. The prior mean of both monetary shock ε_i and mark-up shock ε_π is 1.000 while their posterior means are 0.5756 and 0.8662, respectively.

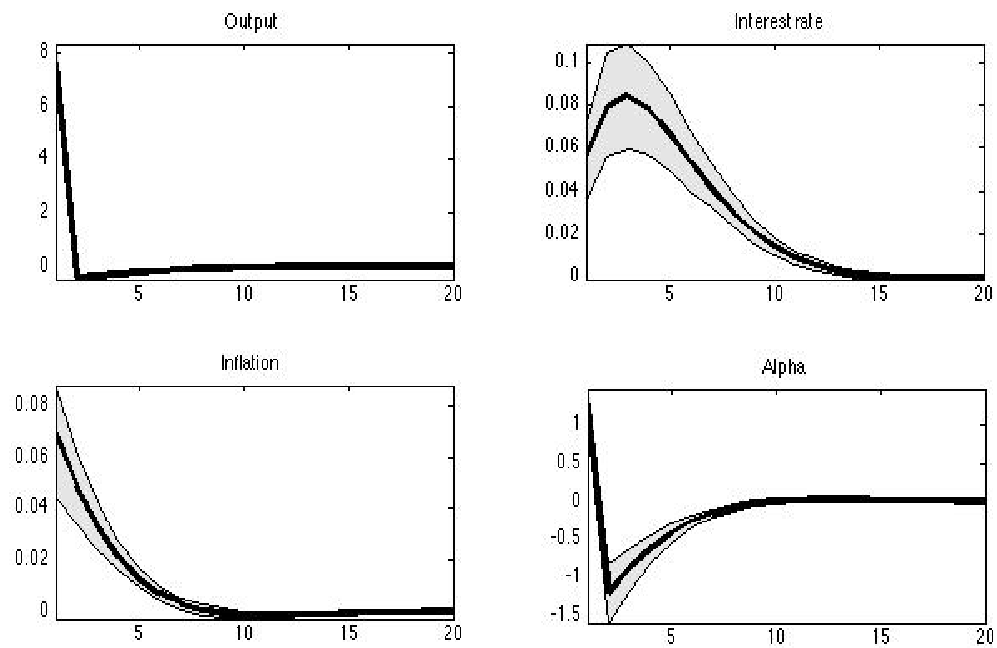


figure 8: Bayesian posterior impulse response to demand shock

Figure 8 reports the posterior impulse responses of macroeconomic variables to a demand shock when annual steady state inflation rate is given by 5 percent for variable α. By comparing figure (8) with figure (2), we can clearly see that two figures reveal rather different responses to demand shocks. First of all, although the shapes of response of output are similar, the posterior impulse response exhibits much greater increase in output compared to that of the regular impulse response function from figure (2). Whereas the output increases by 1 percent in the immediate aftermath of the shock in figure (2), the posterior impulse response of output increases by 8 percent. Furthermore, the posterior impulse response of output lasts longer compared to the impulse response of output in figure (2). One explanation for these observable differences is that the prior mean of the demand shock ε_y is 0.250 whereas the value of its posterior mean equals 8.0725. This striking difference in the magnitude of shock could have resulted in a greater immediate increase of output for the posterior impulse response.

The posterior impulse response of interest rate to demand shock also demonstrates a similar hump shape pattern as the impulse response function of interest rate in figure (2). When the demand shock hits the economy, the interest rate increases immediately by approximately 0.003 percent. According to the posterior impulse response, however, in the immediate aftermath of the shock, the interest rate rises by 0.06 percent.

The posterior response of inflation to demand shock also exhibits a difference in magnitude compared to the impulse response of figure (2). In figure (2), the inflation increases by 0.003, and then gradually returns to its steady state. The posterior impulse response of inflation to demand shock, in contrary, initially rises by approximately 0.07 percent, and then also gradually returns to its steady state value.

Now, let us take a look at the movement of α. The posterior α responds more to the demand shock compared to the α in figure (2). Immediately after the demand shock hits the economy, α in figure (2) increases by 0.1 percent, whereas the posterior α increases by 1 percent. The difference in these two values is rather large, and thus it is possible to conclude that the Bayesian

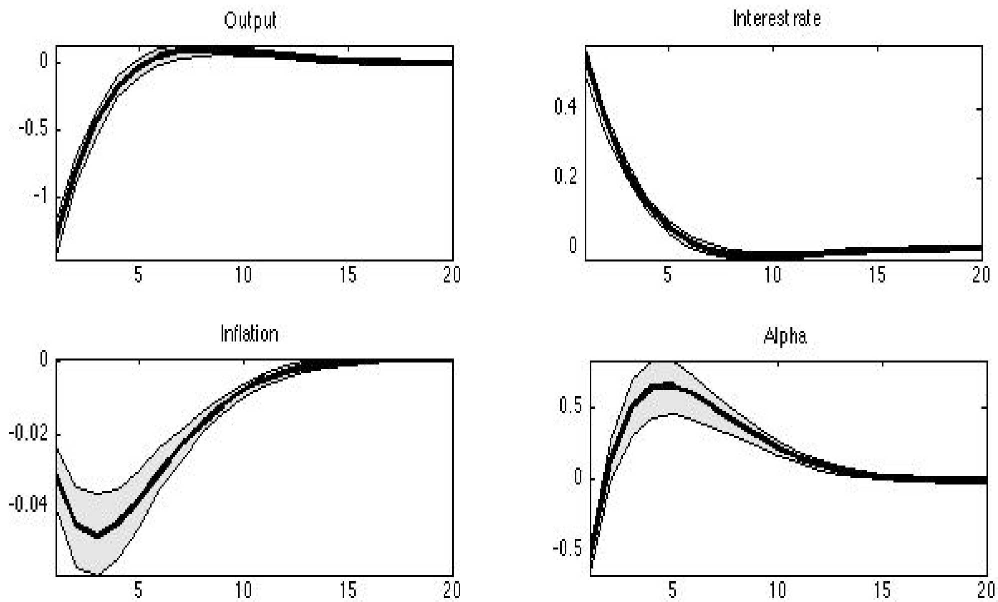


figure 9: Bayesian posterior impulse response to monetary shock

estimation method provides us an alternative view of the fraction of price adjusting firms. When the economy is hit by a demand shock, the demand for goods increases, and according to the Bayesian estimation, the fraction of firms keeping their prices constant increases by 1 percent. Therefore, our estimation using the data reveals that when the demand increases, more firms keep their prices constant. This result indeed makes sense. For instance, *The L.A. Times* of 30 January 1994 had reported that angry consumers threatened to boycott stores that raised prices after an earthquake. The reasoning behind this phenomenon is that customers will deem a price increase not accompanies by a cost increase as unfair. As a result, when demand increases dramatically due to calamity alerts, prices for emergency supplies are kept constant, and store often run out.

Figure (9) displays the posterior impulse response of macroeconomic variables to the monetary shock when the steady state rate of inflation equals 5 percent and when α is variable. First, let us look at the posterior impulse response of output to monetary shock. Again, despite their similarities in shape, the posterior impulse response and the impulse response in figure (3) display differences in terms of the magnitude of response. As it turns out, the posterior impulse response of output falls less than the impulse response of output in figure (3). One plausible explanation for this is that the posterior mean of the interest rate shock is approximately twice smaller than its prior mean. The prior mean of the monetary shock is 1 whereas the posterior mean equals 0.5756. This difference in the size of the shock could have resulted in different responses of output.

The response pattern of interest rate is also as anticipated considering the size of the monetary policy shock. Since the posterior mean of the monetary shock is smaller than its prior mean, the response of the interest rate is also smaller for the posterior impulse response function. While the initial response of the interest rate in figure (3) is an increase by approximately 1 percent, the estimated posterior interest rate increases by 0.6 percent.

Likewise, although the inflation in figure (3) falls by 0.06 percent, the size of the drop in inflation is approximately 0.03. Moreover, the drop in inflation is largest after roughly 3 quarters after the shock first hits the economy. After 3 quarters after the shock, the impulse response function of figure (3) drops by 0.1

percent. The posterior impulse response of inflation, in contrast, displays the largest drop of 0.05 percent.

This observation can be carefully linked with the movement of α. Approximately 5 quarters after the shock, the posterior α reaches its peak 0.7 percent above its steady state, whereas the percent of firms keeping their prices constant is 1 percent above the steady state in figure (3). Since a higher fraction of firms change their prices from the posterior estimation results, and since these price adjustments are likely to accompany price increases, it is more likely that the drop in inflation is smaller in the case of the posterior estimation. In other words, according to our posterior estimation result, a higher fraction of firms increasing their prices offsets the effect of monetary shock that leads to a drop in inflation.

Figure 10 reports the estimated posterior impulse responses of macroeconomic variables to inflation shock when the steady state rate of inflation equals 5 percent and when α is variable. Notice that the response of the estimated posterior output drops by approximately 2.8 percent immediately after the shock. The output in figure (4), in contrast, initially falls by 6 percent. Therefore, according to our estimated posterior impulse response function, in the immediate aftermath of the inflation shock the posterior output responds less than the output of figure (4). This could partly be due to the fact that the estimated posterior mean of ε_π is less than the given prior mean of ε_π. While the posterior mean of ε_π is 0.8662, its prior mean value equals 1. Although the estimated difference in the mean value of the inflation shock may not be large, some of the outcomes from our estimated result could be accounted for.

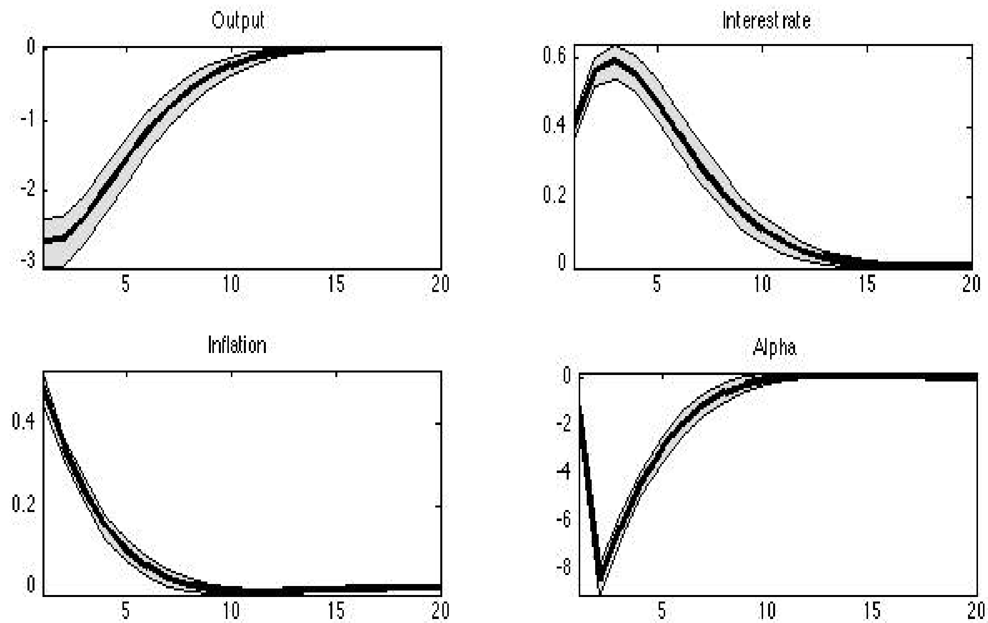


figure 10: Bayesian posterior impulse response to mark-up shock

Just as we have anticipated from the difference in the size of the inflation shock, the estimated posterior interest rate responds less to the shock compared to the interest rate in figure (4). Immediately after the shock, the interest rate in figure (4) rises by 0.5 percent, then reaches its peak (0.85 percent above the steady state) after approximately 3 quarters. The estimated posterior interest rate, in contrast, increases by 0.4 percent, and then reaches its peak (0.6 percent above the steady state) after 3 quarters.

Likewise, the effect of the mark-up shock on the estimated posterior inflation rate is lower than that of figure (4). Right after the shock hits, the posterior inflation increases by 0.5 percent, whereas the inflation in figure (4) rises by 0.6 percent. Furthermore, although the response path of the estimated posterior inflation is always above its steady state value, the inflation in figure (4) falls below its steady state value after 5 quarters, and then gradually returns to its steady state.

The estimated posterior α and the α in figure (4) display analogous impulse response functions, both in terms of the shape and in terms of the magnitude of the response.

5 Comparison with the standard New Keynesian model

5.1 New Keynesian Phillips Curve with zero trend inflation

In this subsection, we compare our estimated results of the behavioral price setting model with the standard 3 equation New Keynesian model. The IS equation and the Taylor rule are given equally as in Rotemberg's (2005) behavioral model. The only difference is in the Phillips curve, which is given by

$$\tilde{\pi}_t = \frac{\beta}{1+\gamma\beta} E_t \tilde{\pi}_{t+1} + \frac{\gamma}{1+\gamma\beta} \tilde{\pi}_{t-1} + \kappa y_t + \upsilon_{\pi,t} \ ,$$

where

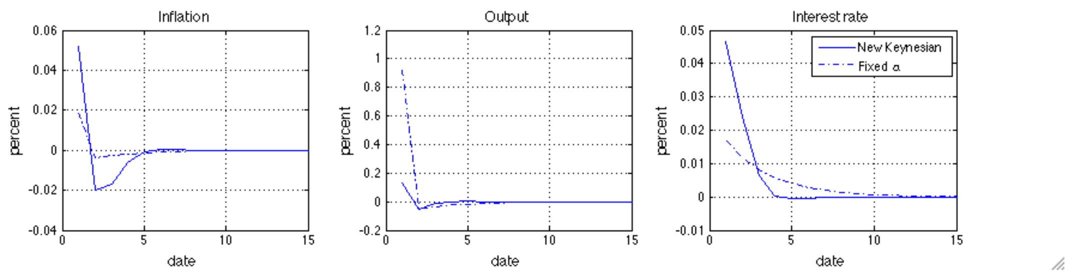
$$v_{\pi,t} = \rho_\pi v_{\pi,t-1} + \varepsilon_{\pi,t}.$$

The shock $\varepsilon_{\pi,t}$ is normally distributed around zero with variance σ_π^2. Specifically, κ is a composite parameter that depends on the degree of price stickiness and firms' production technology, the coefficient γ denotes the degree of price indexation $(0 \leq \gamma \leq 1)$, and the autocorrelation ρ_π $(0 \leq \rho_\pi \leq 1)$ represents the persistence in the supply shock.

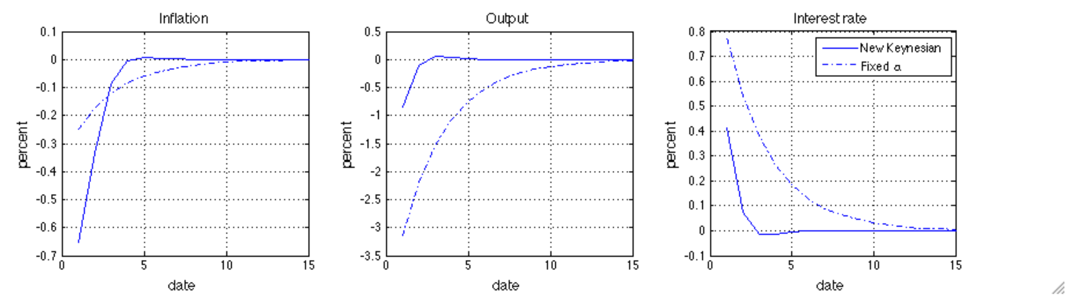
Figure 11 reports the response pattern of inflation, output, and interest rate in the standard New Keynesian 3 equation model. Impulse response for each macroeconomic variable for the behavioral model in the case of fixed α, and steady state inflation rate of 0, is also depicted as a dotted line for the sake of comparison.

Just as anticipated, when the steady state rate of inflation is set to 0 in the behavioral model, the effects of α disappear, and thus the response of macroeconomic variables displays a similar pattern to that of the standard New Keynesian model. Despite their similarities in terms of the shape of response path, the absolute size of the initial response of the behavioral model with 0 steady state inflation is clearly different from that of the New Keynesian model. The first row of figure 11 displays the impulse response of macroeconomic variables to the demand shock. We can see that when the demand shock hits the economy, the inflation and the interest rate of the New Keynesian model respond more than that of the behavioral model. The inflation of the New

Orthogonalized shock to ε_y



Orthogonalized shock to ε_i



Orthogonalized shock to ε_π

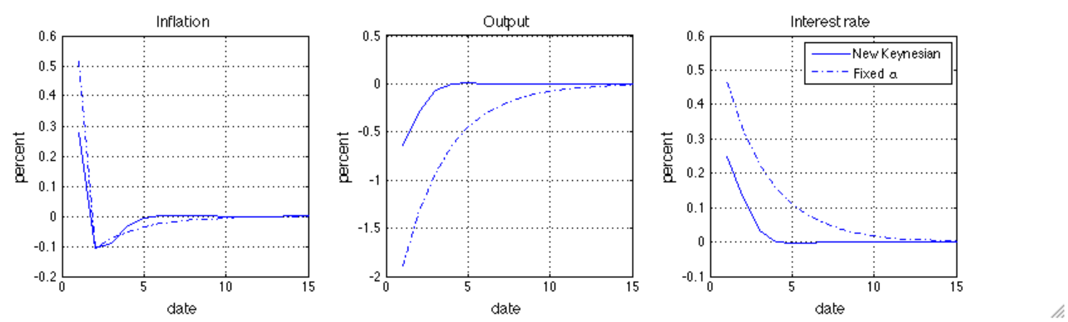


figure 11: Impulse response of inflation, output and interest rate in the New Keynesian model

TABLE 3 – PRIOR DISTRIBUTIONS FOR DSGE MODEL PRAMETERS

Parameters	Prior Mean	Mode	Standard Deviation	t-statistic	Prior	Prior St.Deviation
γ	0.300	0.0190	0.0415	0.4581	Beta	0.2000
κ	0.400	0.0448	0.0004	108.5442	Gamma	0.1000
c_{π}^{i}	0.920	0.7928	0.0176	45.1320	Normal	0.0200
c_{1}^{i}	0.880	0.7210	0.0071	101.4835	Normal	0.0250
β	0.970	0.9889	0.0099	99.5591	Beta	0.0213
ρ_{π}	0.600	0.6189	0.0410	15.1120	Beta	0.1000
θ	1.050	1.0526	0.0091	115.1452	Gamma	0.0250
ε_{y}	0.250	34.2026	2.3357	14.6432	Inv. Gamma	2.0000
ε_{i}	1.000	0.5573	0.0307	18.1614	Inv. Gamma	8.0000
ε_{π}	1.000	2.6372	0.1346	19.5984	Inv. Gamma	8.0000

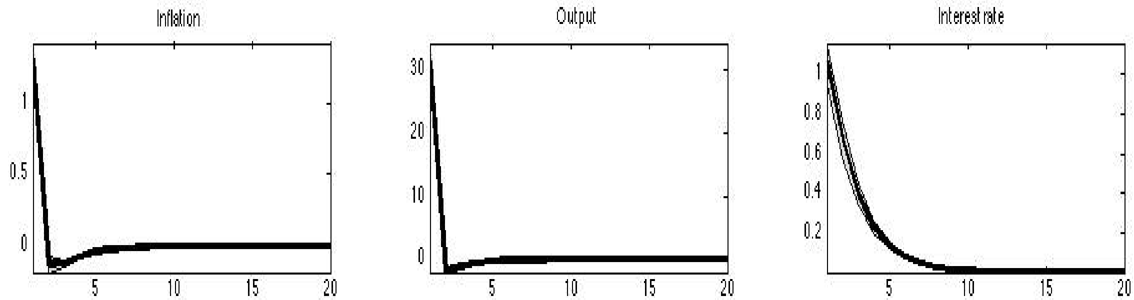
Keynesian model rises by 0.05 percent whereas the inflation of the behavioral model increases by only 0.02 percent. Moreover, approximately 2 quarters after the shock, the inflation falls below the steady state value and returns to its steady state 5 quarters after the shock. Likewise, the interest rate of the New Keynesian model rises by approximately 3 times more than that of the behavioral model. However, we can clearly see that output of the behavioral model responds far more than response of the output of the New Keynesian model. We can see that a demand shock induces output of the behavioral model to rise by 0.9 percent while it only rises by 0.1 percent in the New Keynesian model.

TABLE 4 – PARAMETER ESTIMATION RESULTS

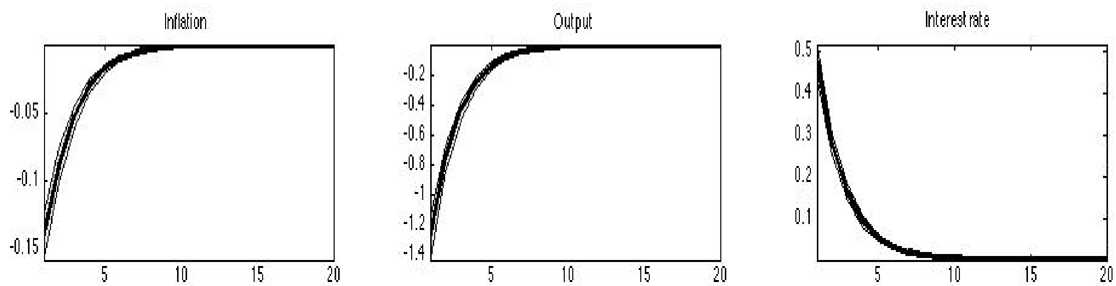
Parameters	Prior Mean	Posterior Mean	Confidence	Interval	Prior	Prior St.Deviation
γ	0.300	0.0527	0.0001	0.1098	Beta	0.2000
κ	0.400	0.0452	0.0448	0.0457	Gamma	0.1000
c_π^i	0.920	0.8087	0.7928	0.8260	Normal	0.0200
c_1^i	0.880	0.7351	0.7210	0.7513	Normal	0.0250
β	0.970	0.9767	0.9550	0.9991	Beta	0.0213
ρ_π	0.600	0.5722	0.4057	0.7417	Beta	0.1000
θ	1.050	1.0455	1.0038	1.0825	Gamma	0.0250
ε_y	0.250	34.4848	31.6494	37.4180	Inv. Gamma	2.0000
ε_i	1.000	0.5881	0.5348	0.6401	Inv. Gamma	8.0000
ε_π	1.000	2.5718	2.2206	2.9378	Inv. Gamma	8.0000

Now let us analyze the impulse responses to the monetary shock. From the second row of figure 11 we can see that the output and the interest rate of the New Keynesian model responds less to a monetary shock than that of the behavioral model. More specifically, the response of the output of the New Keynesian model is approximately 3 times larger than its response in the behavioral model, and the response of the interest rate of the New Keynesian model is twice larger than that of the behavioral model. However, after the immediate aftermath of the monetary shock, inflation of the New Keynesian model drops by 0.65 percent, while it only drops by 0.25 percent in the behavioral model.

Orthogonalized shock to ε_y



Orthogonalized shock to ε_i



Orthogonalized shock to ε_π

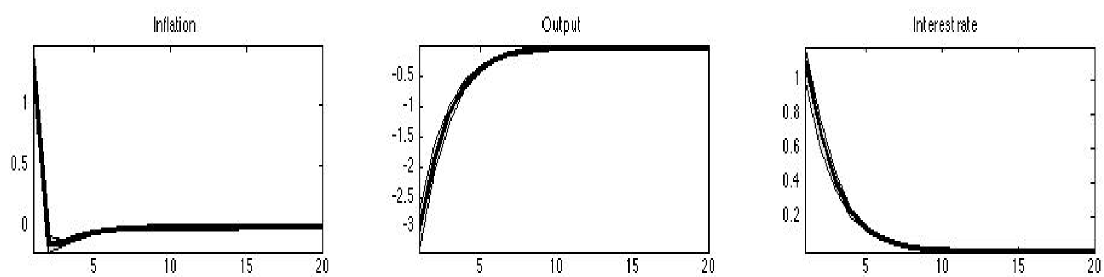


figure 12: Bayesian Posterior IRF for the New Keynesian Model

The impulse response of output and interest rate to inflation shock displays similar pattern with the impulse response of output and interest rate to monetary shock. In both cases, the response of the variables of the behavioral model is larger than that of the New Keynesian model.

Table 3 gives an overview of our assumptions regarding the prior distributions of the estimated parameters. All the variances of the shocks are assumed to follow an Inverted Gamma distribution. Inverted Gamma distribution guarantees a positive variance with a rather large domain.

The coefficient of degree of price indexation, γ, is described by a Beta distribution and has a prior mean of 0.3 with a standard error of 0.0415. κ follows Gamma distribution and is set around 0.4 and has a standard error of 0.0004. The rest of the parameters are described by the same prior information as in table 1.

Table 4 summarizes the estimation results of the posterior distribution of the parameters from the standard New Keynesian model, obtained by the Metropolis-Hastings algorithm. A sample of 50,000 draws was created, were the first 10,000 draws were neglected.

From our Bayesian estimation results, we can see that the prior mean value and the posterior mean value of γ differ significantly. The prior mean value of γ equals 0.3 whereas its posterior mean equals 0.0527. Another interesting observation from the posterior estimation is the posterior mean value of κ. Whereas the prior mean value of κ is 0.4, its posterior mean value equals 0.0452. Since κ denotes the composite parameter that depends on the degree of price stickiness and firms' production technology, a smaller value of κ implies that inflation is less affected by the aggregate output. This in turn implies that according to our posterior estimation, prices are more rigid. The rest of the parameters also display some variation between the prior mean and the posterior mean. The analysis for the rest of the parameters is similar to the analysis given for table 2.

Figure 12 reports the posterior impulse response functions of macroeconomic variables for the standard New Keynesian model. From the comparison of this model's regular impulse response function in figure 11, we can clearly see that despite their alikeness in the shape of the response, the magnitude of the response to shocks in figure 11 and figure 12 differs significantly.

Interestingly, all three variables, namely the inflation, output, and interest rate, show greater response to the demand shock in their posterior estimation. Immediately after the demand shock, the posterior inflation rises by roughly 1 percent. This response of inflation is nearly twice as large as the response of inflation in figure 13. Likewise, the respond of the posterior interest rate is also nearly twice as large as that of figure 13. The posterior estimation of the response of output to demand shock exhibits a striking difference from the prior impulse response. The demand shock raises the posterior output by approximately 30 percent while it raises the prior output by only 0.9 percent.

The magnitude of posterior impulse response of inflation, output and interest rate to monetary shock are all less than their prior impulse response. This may be partly due to the fact that the posterior mean value of themonetary shock is less than its prior mean value. The prior mean value of the monetary shock is 1.000 whereas its posterior mean equals 0.5881. This difference in the size of the monetary shock could have resulted in a weaker response of macroeconomic variables to the shock.

Likewise, a greater posterior mean value of the mark-up shock has resulted in a greater response of the posterior inflation, output and interest rate to the inflation shock. The posterior inflation shock takes the value of 2.5718, which is nearly 2.5 times larger than its prior mean value. The immediate posterior impulse response of inflation to ε_π is roughly 2.5 times larger than that of prior inflation. Similarly, the immediate posterior impulse responses of output and interest rates also display responses that are approximately 2.5 ~ 3 times larger than their prior responses.

5.2 New Keynesian Phillips Curve with Positive Trend Inflation

Now let us compare the impulse response functions of the behavioral model with those of the New Keynesian model when the steady state rate of inflation equals 5 percent. Once again, the IS equation and the Taylor rule are given equally as in Rotemberg's (2005) behavioral model.

Each firm, according to the Calvo framework, adjusts its price in each period with probability $(1-\alpha)$. Suppose that each firm's production function is given by

$$Y_t(i) = A_t H_t(i)^a$$

where a is the labor income share that satisfies $0 < a < 1$.

A firm chooses its price at period t, $P_t(i)$ to maximize the value function such that

$$\max_{P_t(i)} E_t \sum_{j=0}^{\infty} \alpha^j Q_{t,t+j} \left[\left(\frac{P_t(i)}{P_{t+j}}\right)^{1-\theta_{t+j}} Y_{t+j} - \frac{W_{t+j}(i)}{P_{t+j}} \left(\left(\frac{P_t(i)}{P_{t+j}}\right)^{-\theta_{t+j}} Y_{t+j} \right)^{\frac{1}{a}} \right] \quad (23)$$

where $Q_{t,t+j} = \beta^j \left(\frac{C_t}{C_{t+j}}\right)^{-\sigma}$ is the real stochastic discount factor.

The first order condition of this maximization problem is

$$E_t \sum_{j=0}^{\infty} \alpha^j Q_{t,t+j} \left(\theta_{t+j} - 1\right) X_t^{1-\theta_{t+j}} \left[\prod_{k=1}^{j} \Pi_{t+k}\right]^{\theta_{t+j}-1} Y_{t+j} =$$

$$E_t \sum_{j=0}^{\infty} \alpha^j Q_{t,t+j}\, \theta_{t+j} \frac{1}{\alpha} X_t^{-\theta_{t+j}(1+\omega)} \left[\prod_{k=1}^{j} \Pi_{t+k}\right]^{\theta_{t+j}(1+\omega)} Y_{t+j}{}^{1+\omega+\sigma^{-1}} \quad (24)$$

where $1/\prod_{k=1}^{j} \Pi_{t+k} = P_l/P_{l+j}$, and Π_l is the gross inflation rate.

Log-linearizing equation (2) around the steady state, we obtain the optimal relative price that is given by

$$x_t = \left(\frac{1-\beta\alpha\pi^{(\theta+\omega\theta)}}{1+\omega\theta}\right) E_t \sum_{j=0}^{\infty} \beta^j \alpha^j \pi^{j(\theta+\omega\theta)}$$

$$*\left(\left[1 + (1+\omega)\theta \ln\left(\frac{\pi^j}{X}\right)\right] \tilde{\theta}_{t+j} + (\theta + \omega\theta) \sum_{k=1}^{j} \tilde{\pi}_{t+k} + (\omega + \sigma^{-1} + 1) y_{t+j}\right) \quad (25)$$

$$-\frac{1-\beta\alpha\pi^{(\theta-1)}}{1+\omega\theta} E_t \sum_{j=0}^{\infty} \beta^j \alpha^j \pi^{j(\theta-1)} \left(\left[\frac{\theta}{\theta-1} + \theta \ln\left(\frac{\pi^j}{X}\right)\right] \tilde{\theta}_{t+j} + (\theta - 1) \sum_{k=1}^{j} \tilde{\pi}_{t+k} + y_{t+j}\right)$$

where $X_t \equiv P_t^*/P_t$.

The aggregate price level then becomes

$$P_t = \left[(1-\alpha) P_t^{*1-\theta_t} + \alpha P_{t-1}^{1-\theta_t}\right]^{\frac{1}{1-\theta_l}}.$$

Rewriting this expression yields

$$(1-\alpha)X_t^{(1-\theta_t)} + \alpha\Pi_t^{\theta_t - 1} = 1. \tag{26}$$

Notice that this equation is equivalent to equation (18) of the behavioral model.

$X > 1$ when the steady state rate of inflation is greater than 1. This is due to the fact that in the steady state, the presence of trend inflation erodes relative prices determined by firms in the past. Log linearization of equation (26) yields

$$\tilde{\pi}_t = \frac{1-\gamma}{\gamma}x_t + \frac{\theta}{\theta-1}\left[\frac{1-\gamma}{\gamma}\frac{1}{\theta-1}\ln\left(\frac{1-\alpha}{1-\gamma}\right) - \ln\pi\right]\tilde{\theta}_t \tag{27}$$

where $\gamma = \alpha\pi^{\theta-1}$.

Equation (27) implies that inflation depends on the price set by firms in the current period (given by (25)), and a second term proportional to log-deviations in competitiveness. This second term is present only if the trend inflation is non-zero. Using equations (25) and (27), the reduced-form expression for the New Keynesian Phillips curve in the presence of positive trend inflation becomes

$$\tilde{\pi}_t = a_1^{\pi}E_t\tilde{\pi}_{t+1} + a_2^{\pi}E_t\tilde{\pi}_{t+2} + S_{PI}y_t + a_1^{y}E_t y_{t+1} \tag{28}$$

with the following expressions for the coefficients:

$$a_1^{\pi} = \gamma_1 + \gamma_2 + \frac{1-\gamma}{\gamma}\frac{1}{1+\omega\theta}[(\theta+\omega\theta)\gamma_2 - (\theta-1)\gamma_1];$$

TABLE 5 – PRIOR DISTRIBUTIONS FOR DSGE MODEL PRAMETERS

New Keynesian Model with positive steady state inflation

Parameters	Prior Mean	Posterior Mean	Confidence	Interval	Prior	Prior St.Deviation
σ	1.050	1.0719	0.0190	56.5551	Gamma	0.0250
c_π^i	0.920	0.7928	0.0118	67.0570	Normal	0.0200
c_1^i	0.880	0.7210	0.0042	172.9377	Normal	0.0250
β	0.970	0.9858	0.0137	72.0290	Beta	0.0213
ρ_π	0.4300	0.4286	0.0090	47.4004	Beta	0.0150
θ	6.500	7.6389	0.0116	660.0885	Normal	0.2300
ω	1.420	1.4169	0.0402	35.2047	Normal	0.0500
ε_y	0.250	8.1531	0.4475	18.2179	Inv. Gamma	2.0000
ε_i	1.000	0.5583	0.0298	18.7099	Inv. Gamma	8.0000
ε_π	1.000	1.5803	0.0929	17.0082	Inv. Gamma	8.0000

$$a_2^\pi = -\frac{\gamma_1\gamma_2}{\gamma};$$

$$S_{PI} = \frac{1-\gamma}{\gamma}\frac{1}{1+\omega\theta}\left[(\omega+\sigma^{-1}+1)(1-\gamma_2)-(1-\gamma_{1)}\right];$$

$$a_1^y = -\frac{1-\gamma}{\gamma}\frac{1}{1+\omega\theta}\left[(\omega+\sigma^{-1}+1)\gamma_1(1-\gamma_2)-\gamma_2(1-\gamma_{1)}\right];$$

$$\gamma = \alpha\pi^{\theta-1};$$

$$\gamma_1 = \alpha\beta\pi^{\theta-1}; \quad \gamma_2 = \alpha\beta\pi^{\theta+\omega\theta}.$$

TABLE 6 – PARAMETER ESTIMATION RESULTS

New Keynesian Model with positive steady state inflation

Parameters	Prior Mean	Posterior Mean	Confidence	Interval	Prior	Prior St.Deviation
σ	1.050	1.0721	1.0317	1.1122	Gamma	0.0250
c_π^i	0.920	0.8078	0.7928	0.8243	Normal	0.0200
c_1^i	0.880	0.7260	0.7210	0.7323	Normal	0.0250
β	0.970	0.9711	0.9429	0.9988	Beta	0.0213
ρ_π	0.4300	0.4294	0.4067	0.4535	Beta	0.0150
θ	6.500	7.6387	7.6219	7.6558	Normal	0.2300
ω	1.420	1.4194	1.3402	1.4994	Normal	0.0500
ε_y	0.250	8.2177	7.3106	9.0506	Inv. Gamma	2.0000
ε_i	1.000	0.5789	0.5307	0.6255	Inv. Gamma	8.0000
ε_π	1.000	1.5936	1.4360	1.7559	Inv. Gamma	8.0000

Details of the derivation of the Phillips curve with positive inflation is provided in Appendix.

Table 5 and 6 report an overview of the prior distributions of the parameters of the New Keynesian model with positive trend inflation, and their estimation results.

Figure 13 reports the impulse response functions of macroeconomic variables for the New Keynesian model when trend inflation equals 5 percent. The impulse responses of the behavioral model are also displayed in a dotted line for the ease of comparison. As we have anticipated, the impulse response functions

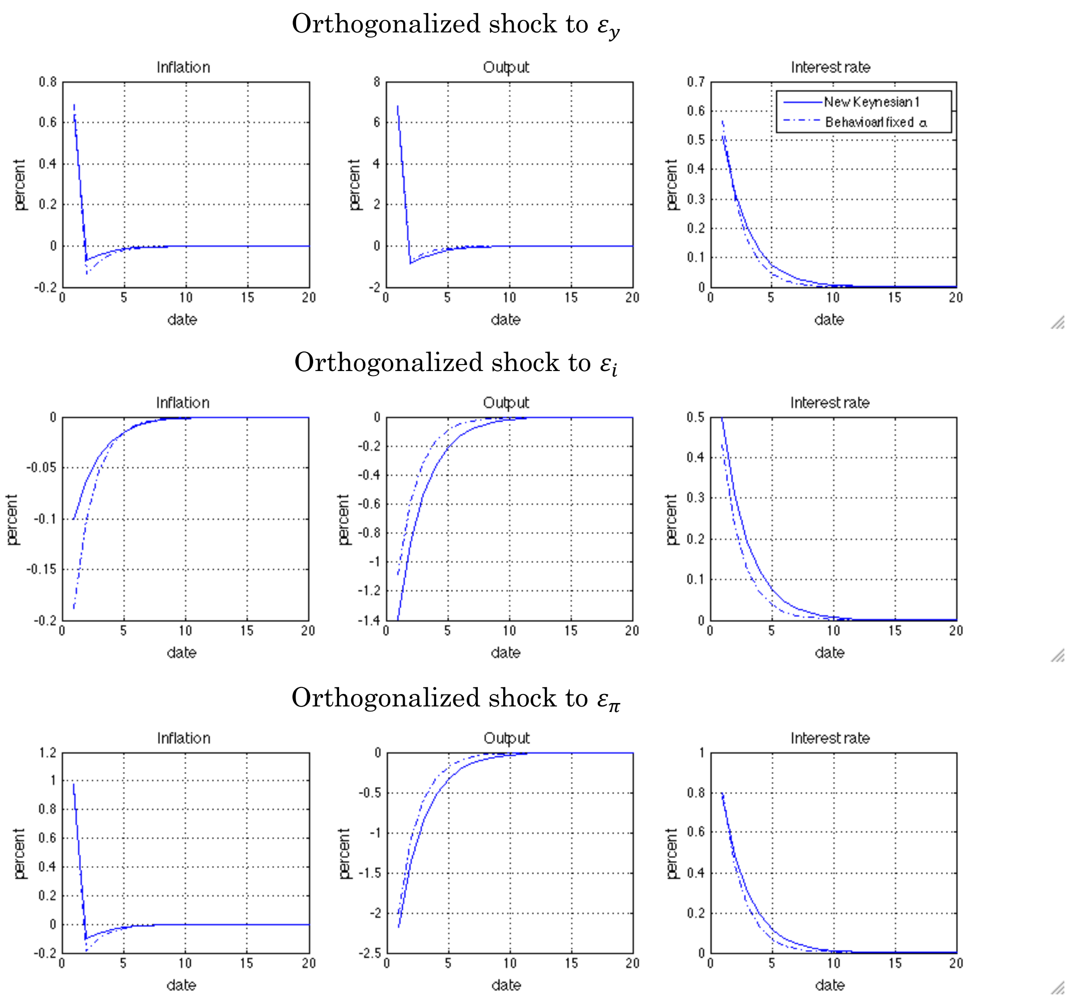


figure 13: Bayesian Posterior IRF for the New Keynesian Model with Positive Steady State Inflation

Details of the derivation of the Phillips curve with positive inflation is provided in Appendix.

of two different model display strikingly similar patterns. The only notable difference between the impulse responses of two models can be seen in the response patterns to monetary shocks.

In the immediate aftermath of the monetary shock, the inflation of the New Keynesian model drops by 0.1 percent whereas the inflation of the behavioral model decreases by roughly 0.2 percent.

However, the output and the interest rate of the New Keynesian model shows greater response to the monetary shock than that of the behavioral model. Immediately after the monetary shock, the output of the New Keynesian model drops by 1.4 percent while its counterpart of the behavioral model drops by 1.1 percent. Moreover, the response of the interest rate of the New Keynesian model is also slightly larger than that of the behavioral model.

6 Conclusion

In this paper, we analyzed the nature of price stickiness by analyzing the price setting behavior of firms. Although standard macroeconomics often rely on fixed administrative costs of price adjustment to account for price rigidity, we have studied several recent models that attempt to explain price rigidity though psychological and emotional aspects that affect people's decisions. In particular, we have shown that Rotembeg's model of consumer anger at price increases can give explanations for the observed price stickiness. Moreover, thorough Bayesian estimation methods, we analyzed how macroeconomic variables respond to demand, inflation, and monetary shocks under such behavioral price setting. The comparison of estimated results to the results of the standard New Keynesian model allowed us to conclude that when the steady state rate of inflation equals zero, the behavioral model and the standard New Keynesian model display similar impulse response patterns, albeit they exhibit some differences in the magnitude of the response. When the steady state rate of inflation is positive, the impulse response functions of the behavioral and the New Keynesian model displayed strikingly similar patterns and responses. For future research, we hope to incorporate capital into Rotemberg's behavioral price setting model and see by how much the estimated results would differ from the estimated results of the Smets and Wouters' (2007) Calvo price setting model.

7 Appendix

A. Bayesian Estimation of DSGE Models

Bayesian statistics offers a subjective view about probability in a sense that it allows to incorporate prior information from outside the samples. In practice, Bayesian statistics usually points to constructing estimates of the distribution of unobserved parameters conditional on the data.

Consider a model with a vector of parameters θ. The Bayesian approach to parameter estimation is to treat θ as a random variable. Before observing the actual data, a researcher may have prior information about the parameters based on logic, intuition, or past analysis. These initial ideas about the parameter, called *prior* distributions, are represented by a probability density on θ and is denoted by $p(\theta)$. After gathering data $Y = y_{1,} \ldots, y_N$, the researcher updates his ideas about θ based on the gathered sample information. This updated idea about θ is represented by a new probability density, $p(\theta|Y)$, and is called the *posterior* distribution. Since this posterior distribution incorporates the information from the observed sample, it obviously depends on Y.

The equation that shows how the researcher's ideas about θ change after observing the data is established by Bayes' rule. According to Bayes' theorem,

$$p(\theta|Y)p(Y) = p(Y|\theta)p(\theta)$$

which implies that

$$p(\theta|Y) = \frac{p(Y|\theta)p(\theta)}{p(Y)}.$$

Since the marginal probability of , $p(Y)$, is a constant with respect to θ, it can be stated that the posterior distribution is proportional to the prior distribution times the likelihood function:

$$p(\theta|Y) \propto p(Y|\theta)p(\theta).$$

In Bayesian data analysis, one approach to apply a model to data is to find parameter estimates that maximize the posterior probability of the parameters given the data, i.e. the mode of the posterior distribution. This procedure is similar to the maximum likelihood estimation procedure, but differs in a sense that the prior over parameters will influence parameter estimation. Another approach in Bayesian analysis, which we applied in this paper, is posterior sampling. Unlike the first approach that simply finds the mode of the posterior distribution, the goal is to characterize the full posterior distribution. In many cases, we are unable to obtain analytic expressions for the posterior distribution, and thus have to resort to sampling techniques, such as Markov Chain Monte Carlo (MCMC), to obtain samples from posterior distribution. The samples obtained from MCMC can be used to calculate various statistics, such as mean, variances, and other moments of the distribution. The most general algorithm for simulating $p(\theta|Y)$ is the Metropolis sampler.

The Random-Walk Metropolis Algorithm

The goal of this procedure is to sample from the posterior distribution. The Metropolis sampler generates a Markov chain that produces a sequence of values of parameter:

$$\theta_1 \rightarrow \theta_2 \rightarrow \ldots \rightarrow \theta_t \rightarrow \cdots$$

where θ_t denotes the state of a Markov chain at iteration *t.* The samples from the chain, after the burn-in, reflect samples from the posterior distribution. The following describes the algorithm of the steps of the Metropolis sampler.

1. Set $t = 1$

2. Generate an initial arbitrary value of θ_0

3. Update from θ_t to θ_{t+1} by

   3.1 Generate $\theta^* \sim N(\theta_t, \Sigma)$,

   3.2 Define

$$\alpha = \min\left(\frac{p(Y|\theta^*)}{p(Y|\theta_t)}, 1\right)$$

   3.3 Generate u from a Uniform (0, 1) distribution

   3.4 If $u \leq \alpha$, accept the proposal and set $\theta_{t+1} = \theta^*$, else set $\theta_{t+1} = \theta_t$.

4. Repeat Step 3 T times.

Now we know how to find the posterior distribution of the vector of parameters θ. Another issue that arises when conducting a Bayesian estimation of a DSGE model is the evaluation of the likelihood function.

Given initial parameter values, the Kalman filter can be used to recursively construct the likelihood function for state space models. The likelihood function can be expressed in terms of the one-step ahead forecast errors, conditional on the initial observations, and of their recursive variance, both of which can be obtained with the use of the Kalman filter.

B. Tables and Figures

Figure B.1-I: Priors and Posteriors of the Behavioral Model when the steady state rate of inflation equals 5 percent

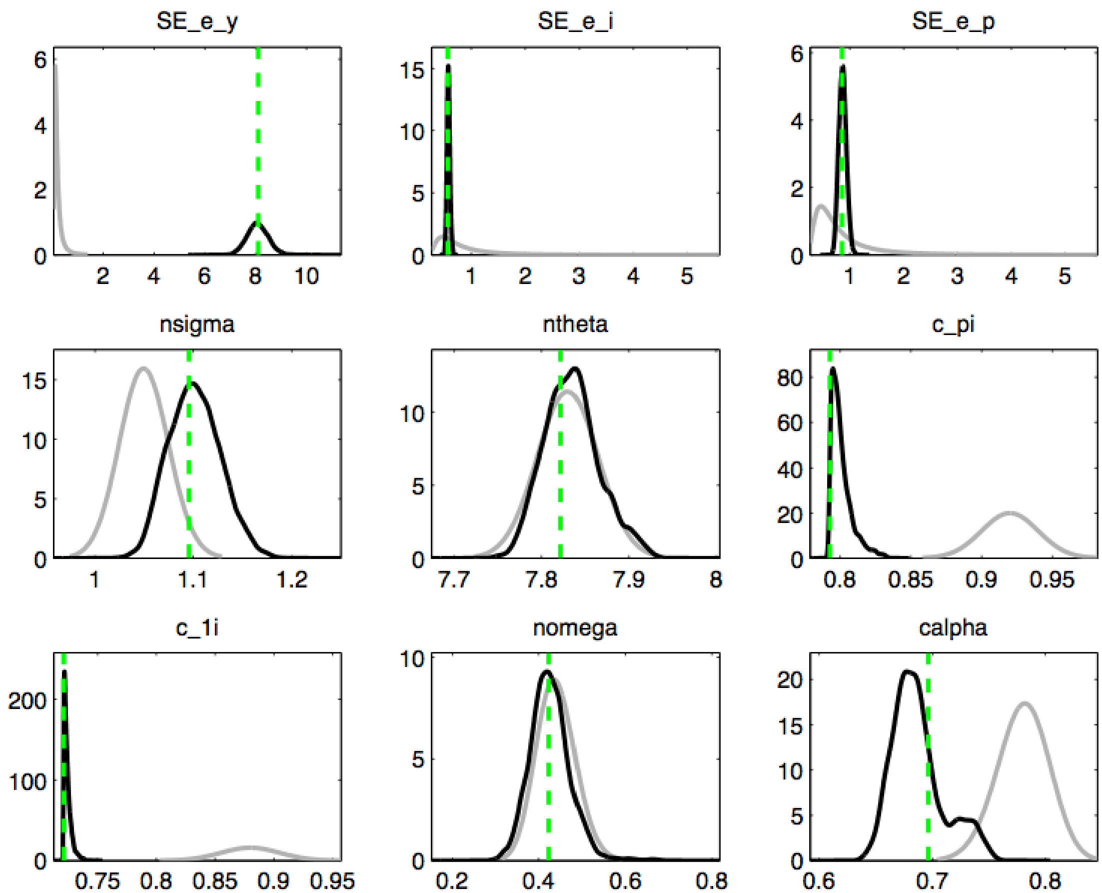


Figure B.1-II: Priors and Posteriors of the Behavioral Model when the steady state rate of inflation equals 5 percent

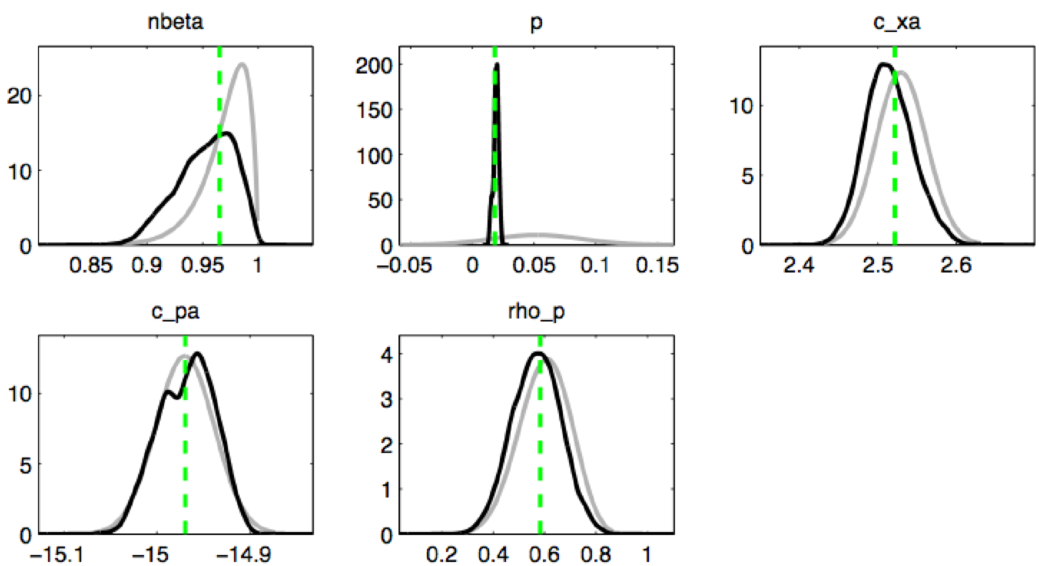


Figure B.2: Smoothed shocks of the Behavioral Model

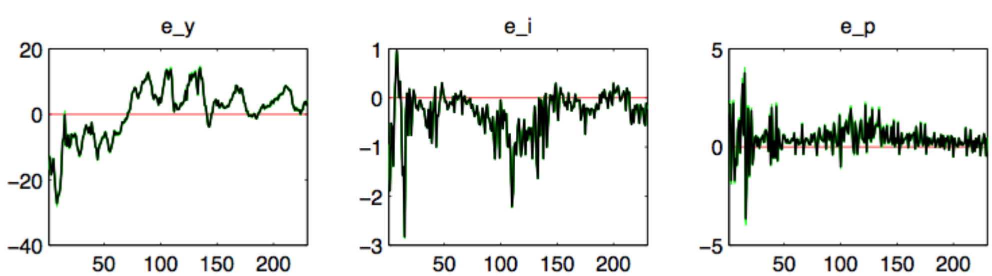


Figure B.3-I: Univariate Diagnostic of the Behavioral Model (Brooks and Gelman 1998)

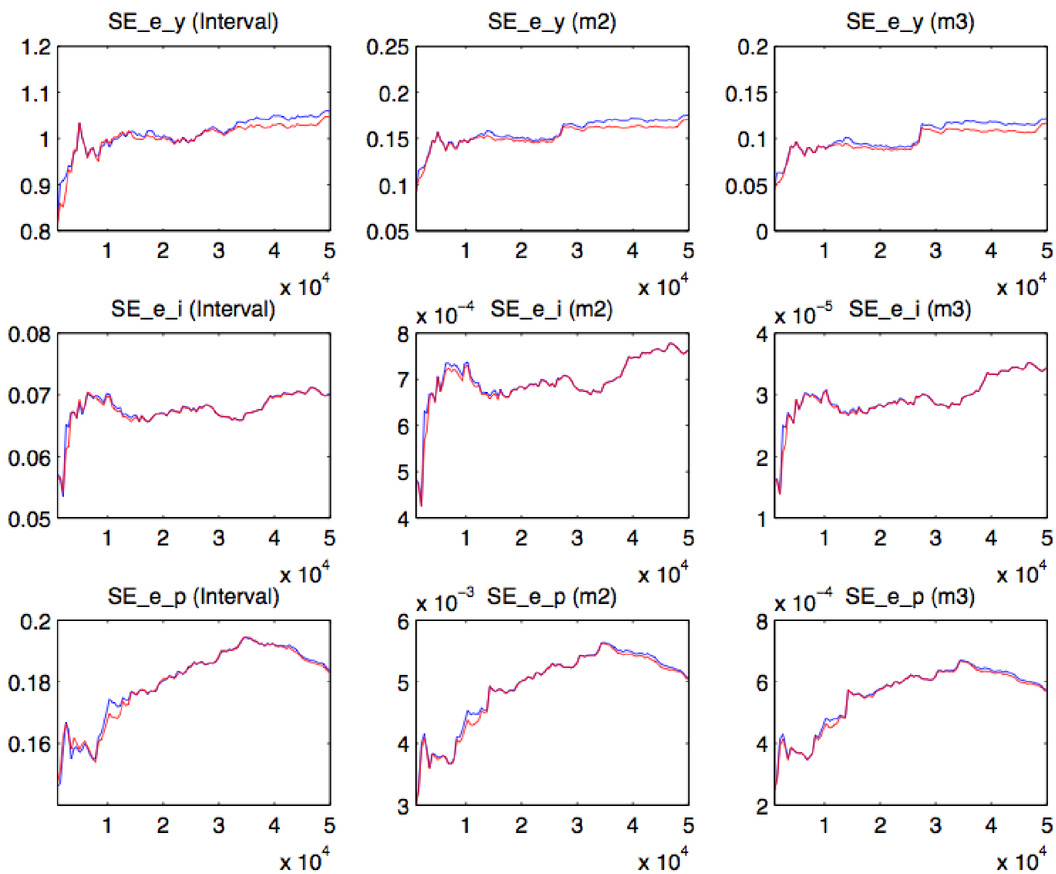


Figure B.3-II: Univariate Diagnostic of the Behavioral Model (Brooks and Gelman 1998)

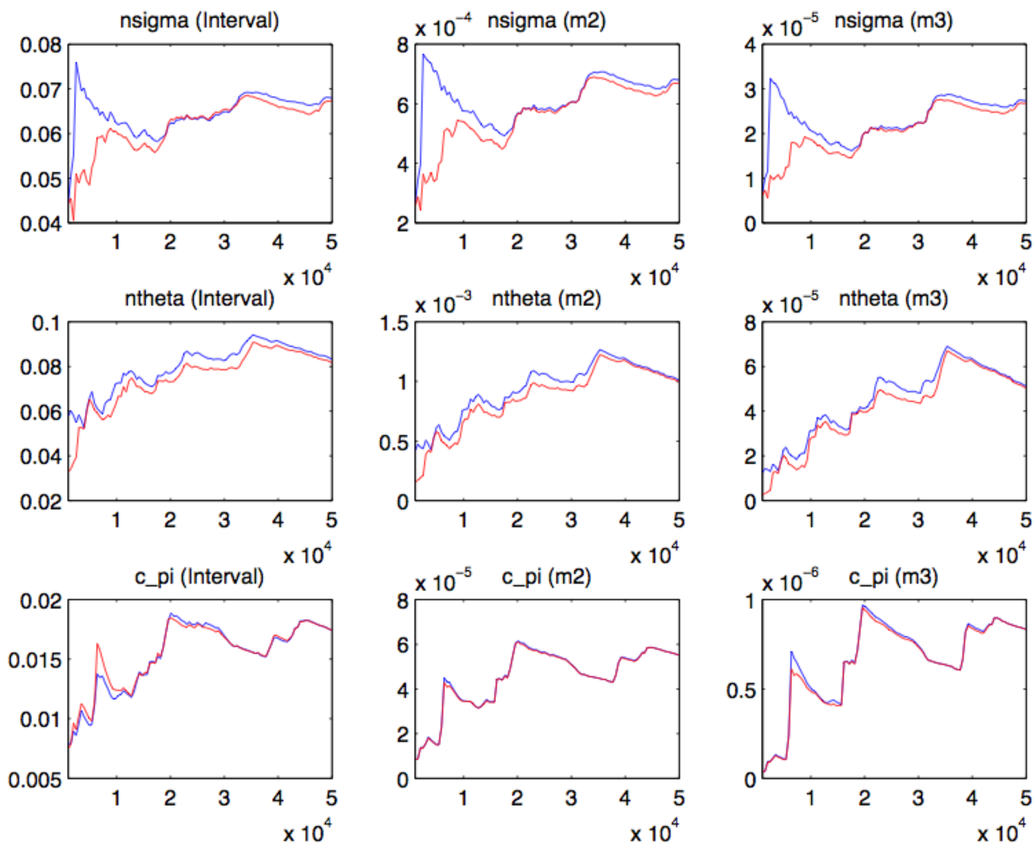


Figure B.3-III: Univariate Diagnostic of the Behavioral Model (Brooks and Gelman 1998)

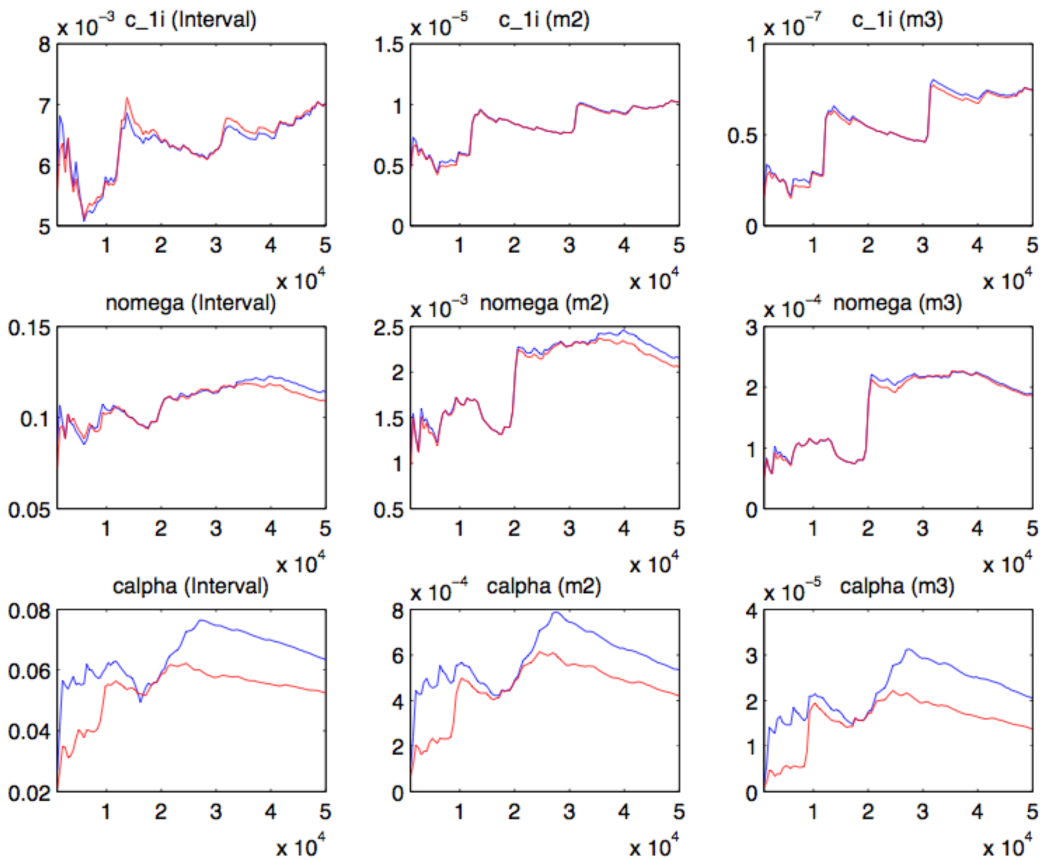


Figure B.3-IV: Univariate Diagnostic of the Behavioral Model (Brooks and Gelman 1998)

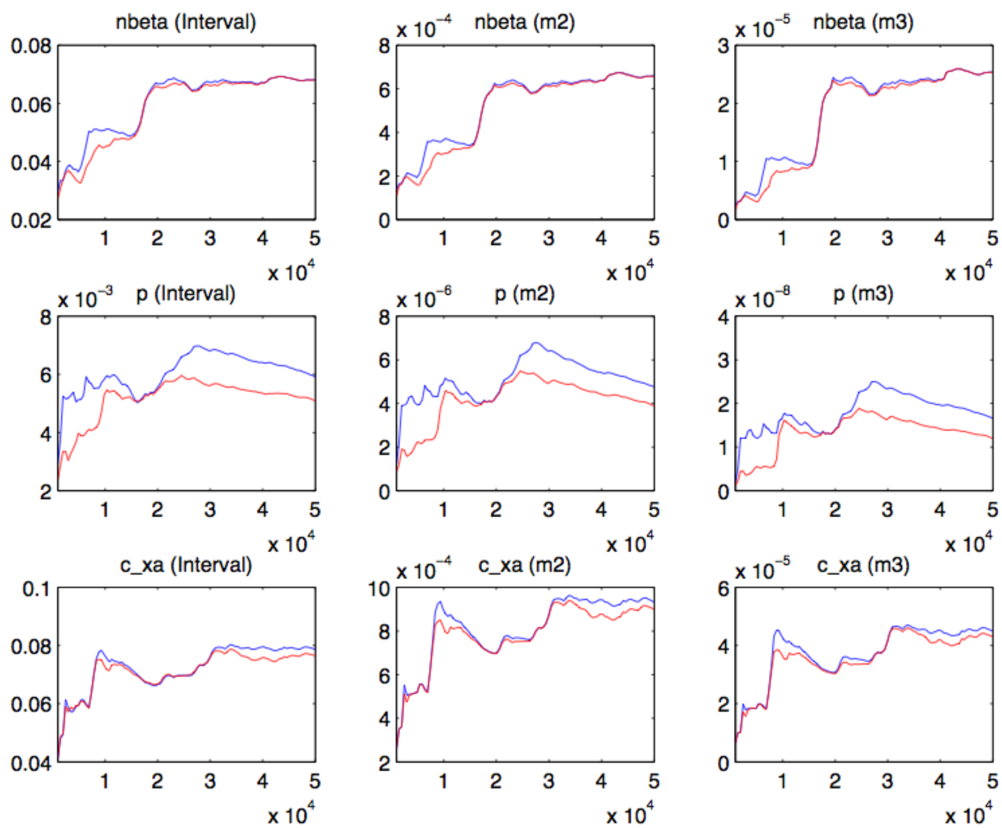


Figure B.3-V: Univariate Diagnostic of the Behavioral Model (Brooks and Gelman 1998)

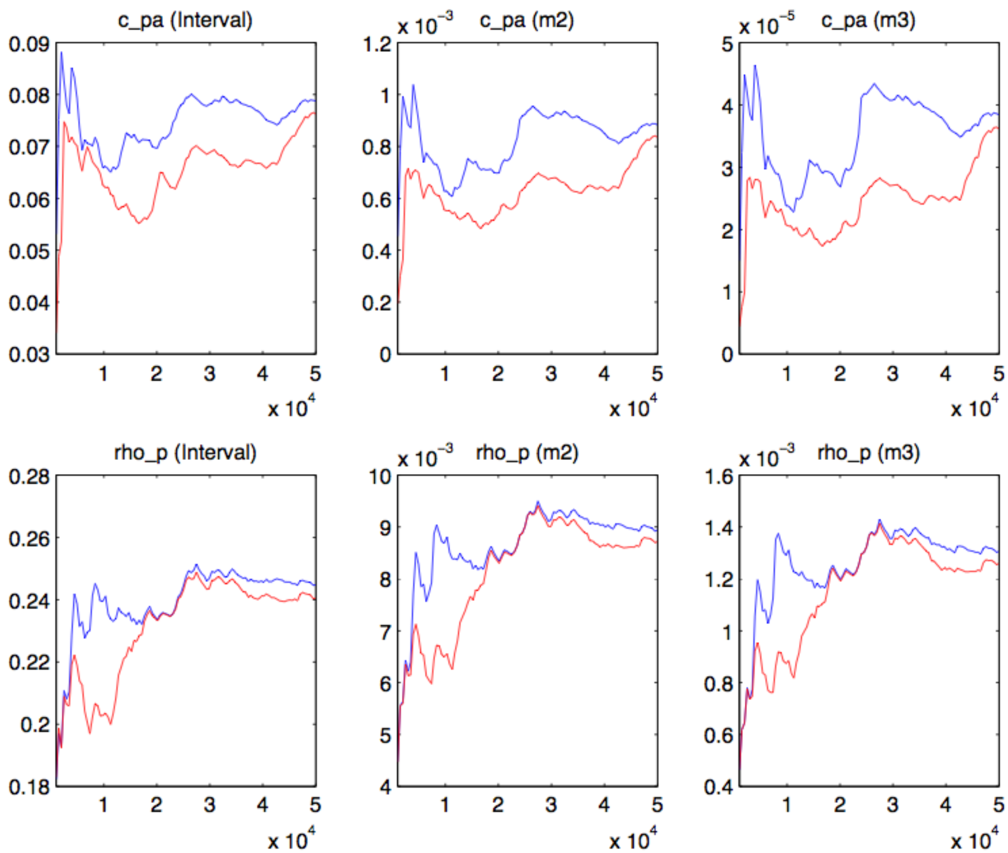


Figure B.4: Multivariate Diagnostic of the Behavioral Model

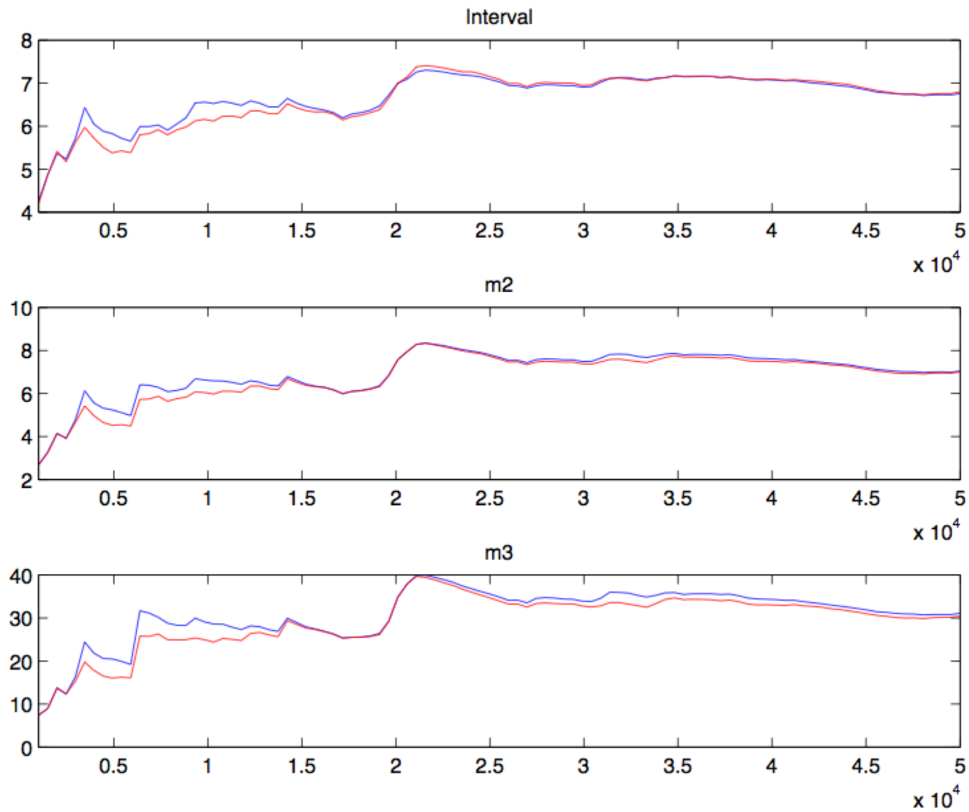


TABLE B.7 – PRIOR DISTRIBUTIONS FOR DSGE MODEL PRAMETERS

Behavioral Model with fixed alpha when steady state inflation rate is 5 percent

Parameters	Prior Mean	Mode	Standard Deviation	t-statistic	Prior	Prior St.Deviation
σ	1.050	1.0701	0.0205	52.2535	Gamma	0.0250
θ	7.830	7.8303	0.0233	335.9718	Gamma	0.0350
c_{π}^{i}	0.920	0.8082	0.0105	76.7408	Normal	0.0200
c_{1}^{i}	0.880	0.7210	0.0046	155.2753	Normal	0.0250
ω	0.440	0.4444	0.0183	24.3517	Gamma	0.0450
α	0.780	0.7837	0.0071	109.8375	Beta	0.0230
β	0.970	0.9839	0.0093	105.8111	Beta	0.0213
π	0.052	-0.0419	0.0057	7.2924	Normal	0.0360
c_{X}^{α}	2.530	2.5300	0.0199	127.1644	Gamma	0.0323
c_{π}^{α}	-14.970	-14.9700	0.0219	683.6975	Normal	0.0315
ρ_{π}	0.600	0.5910	0.0462	12.7963	Beta	0.1000
ε_{y}	0.250	8.3527	0.6158	13.5645	Inv. Gamma	2.0000
ε_{i}	1.000	0.5719	0.0284	20.1265	Inv. Gamma	8.0000
ε_{π}	1.000	2.0912	0.1678	12.4590	Inv. Gamma	8.0000

TABLE B.8 – PARAMETER ESTIMATION RESULTS

Behavioral Model with fixed alpha when steady state inflation rate is 5 percent

Parameters	Prior Mean	Posterior Mean	Confidence	Interval	Prior	Prior St.Deviation
σ	1.050	1.0720	1.0307	1.1118	Gamma	0.0250
θ	7.830	7.8296	7.7755	7.8883	Gamma	0.0350
c_{π}^{i}	0.920	0.8162	0.7928	0.8387	Normal	0.0200
c_{1}^{i}	0.880	0.7263	0.7210	0.7330	Normal	0.0250
ω	0.440	0.4448	0.3749	0.5205	Gamma	0.0450
α	0.780	0.7786	0.7434	0.8138	Beta	0.0230
β	0.970	0.9695	0.9411	0.9983	Beta	0.0213
π	0.052	-0.0361	-0.0522	-0.0205	Normal	0.0360
c_{X}^{α}	2.530	2.5293	2.4778	2.5832	Gamma	0.0323
c_{π}^{α}	-14.970	-14.9704	-15.0221	-14.9184	Normal	0.0315
ρ_{π}	0.600	0.5959	0.4345	0.7745	Beta	0.1000
ε_{y}	0.250	8.2716	7.1680	9.3424	Inv. Gamma	2.0000
ε_{i}	1.000	0.5863	0.5335	0.6264	Inv. Gamma	8.0000
ε_{π}	1.000	2.1245	1.8020	2.4542	Inv. Gamma	8.0000

Note: The posterior distribution is obtained using the Metropolis-Hastings algorithm

C. Derivation of the closed-form New Keynesian Phillips Curve under positive trend inflation

In order to obtain the closed-form New Keynesian Phillips curve under positive trend inflation, we set terms $\tilde{\theta}_{t+j} = 0$ in (25), and use the following relations where L^{-1} is the lead operator:

$$\sum_{j=0}^{\infty} \gamma_1^j y_{t+j} = \sum_{j=0}^{\infty} (\gamma_1 L^{-1})^j y_t = \frac{1}{1-\gamma_1 L^{-1}} y_t \tag{C-1}$$

$$\sum_{j=1}^{\infty} \gamma_1^j \sum_{k=1}^{j} \tilde{\pi}_{t+k} = \frac{\gamma_1}{1-\gamma_1} \frac{1}{1-\gamma_1 L^{-1}} \tilde{\pi}_{t+1} \tag{C-2}$$

where $\gamma_1 = \alpha\beta\pi^{\theta-1}$ and $\gamma_2 = \alpha\beta\pi^{\theta+\omega\theta}$.

Then, equation (25) can be rewritten as

$$\begin{aligned}
&(1+\omega\theta)x_t = \\
&(1-\gamma_2)E_t\left[(\theta+\omega\theta)\sum_{j=1}^{\infty}\gamma_2^j\sum_{k=1}^{j}\tilde{\pi}_{t+k} + (1+\omega+\sigma^{-1})\sum_{j=0}^{j}\gamma_2^j y_{t+j}\right] \\
&\qquad -(1-\gamma_1)E_t\left[(\theta-1)\sum_{j=1}^{\infty}\gamma_1^j\sum_{k=1}^{j}\tilde{\pi}_{t+k} + \sum_{j=0}^{j}\gamma_1^j y_{t+j}\right]
\end{aligned} \tag{C-3}$$

Using (C-1) ~ (C-3), we get

$$\begin{aligned}
(1+\omega\theta)x_t = {}& \frac{1}{1-\gamma_2 L^{-1}} E_t[\gamma_2(\theta+\omega\theta)\tilde{\pi}_{t+1} + (1-\gamma_2)(1+\omega+\sigma^{-1})y_t] \\
& - \frac{1}{1-\gamma_1 L^{-1}} E_t\left[\gamma_1(\theta-1)\tilde{\pi}_{t+1} + (1-\gamma_1)y_t\right]
\end{aligned} \tag{C-4}$$

Using (C-4) and (27), and multiplying through terms involving the lead operator, we get the New Keynesian Phillips curve with positive inflation as

$$\tilde{\pi}_t = a_1^{\pi} E_t \tilde{\pi}_{t+1} + a_2^{\pi} E_t \tilde{\pi}_{t+2} + S_{PI} y_t + a_1^{y} E_t y_{t+1}$$

with the following expressions for the coefficients:

$$a_1^{\pi} = \gamma_1 + \gamma_2 + \frac{1-\gamma}{\gamma}\frac{1}{1+\omega\theta}[(\theta+\omega\theta)\gamma_2 - (\theta-1)\gamma_1];$$

$$a_2^{\pi} = -\frac{\gamma_1\gamma_2}{\gamma};$$

$$S_{PI} = \frac{1-\gamma}{\gamma}\frac{1}{1+\omega\theta}\left[(\omega+\sigma^{-1}+1)(1-\gamma_2) - (1-\gamma_{1)}\right];$$

$$a_1^{y} = -\frac{1-\gamma}{\gamma}\frac{1}{1+\omega\theta}\left[(\omega+\sigma^{-1}+1)\gamma_1(1-\gamma_2) - \gamma_2(1-\gamma_{1)}\right];$$

$$\gamma = \alpha\pi^{\theta-1};$$

$$\gamma_1 = \alpha\beta\pi^{\theta-1};$$

$$\gamma_2 = \alpha\beta\pi^{\theta+\omega\theta}.$$

Behavioral model with variable α and steady state inflation of 5 percent

MATRIX OF COVARIANCE OF EXOGENOUS SHOCKS

Variables	e_y	e_i	e_p
e_y	1.000000	0.000000	0.000000
e_i	0.000000	1.000000	0.000000
e_p	0.000000	0.000000	1.000000

POLICY AND TRANSITION FUNCTIONS

	ninfla	y	i	nalpha
i(-1)	-0.055173	-3.737715	0.850344	-1.642474
ninfla(-1)	0.648899	-6.773044	0.584009	-17.835685
e_y	0.003002	0.968670	0.002701	0.089356
e_i	-0.061304	-4.153017	0.944827	-1.824971
e_p	0.581330	-6.067777	0.523197	-2.540410

THEORETICAL MOMENTS

VARIABLE	MEAN	STD. DEV.	VARIANCE
ninfla	0.0000	0.7604	0.5783
y	0.0000	13.6646	186.7212
i	0.0000	2.4940	6.2202
nalpha	0.0000	15.2215	231.6935

VARIANCE DECOMPOSITION (in percent)

	e_y	e_i	e_p
ninfla	0.00	9.47	90.53
y	0.50	19.27	80.22
i	0.00	35.88	64.12
nalpha	0.01	4.09	95.91

MATRIX OF CORRELATIONS

Variables	ninfla	y	i	nalpha
ninfla	1.0000	-0.5071	0.1905	-0.6499
y	-0.5071	1.0000	-0.9396	0.7655
i	0.1905	-0.9396	1.0000	-0.6214
nalpha	-0.6499	0.7655	-0.6214	1.0000

COEFFICIENTS OF AUTOCORRELATION

Order	1	2	3	4	5
ninfla	0.6144	0.3372	0.1467	0.0230	-0.0512
y	0.8322	0.6666	0.5135	0.3805	0.2706
i	0.8843	0.7417	0.5956	0.4598	0.3415
nalpha	0.7464	0.4490	0.2372	0.0934	0.0016

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국문초록

거시경제학이 합리성으로부터 벗어나야 한다는 주장이 제기되면서, 많은 경제학자들이 인간의 행동과 심리의 관찰을 통하여 경제 현실을 설명하려는 시도를 해왔다. 정통 거시경제학에서는 가격 경직성을 메뉴비용으로 설명하기도 하며, 중첩가격모형을 통해 가격의 경직성을 설명하는 것이 대세를 이룬다. 그러나 마케팅 조사에 따르면 기업들이 가격을 경직적으로 유지하는 주 된 이유는 가격을 올림으로 고객들의 심기를 불편하게 하는 일이 발생하지 않도록 하기 위함으로 드러났다. 가격상승으로 인해 화가 난 소비자들이 불매 운동을 벌이면 기업 입장에서 큰 손해이기 때문이다. 본 논문에서는 최근의 행동 경제학적 모형들을 살펴본다. 특히 행동적 측면이 부가된 동태적 확률적 일반 균형 모형들을 위주로 살펴본다. 이러한 행동적 가격 책정 모형의 현실 설명력을 확인하기 위해 본 논문에서는 Rotemberg (2005)의 모형을 로그-선형 하여 데이터를 이용하여 베이지안 추정을 한다. 베이지안 추정을 통해 얻어진 결과를 일반적인 뉴케인지안 모형과 비교를 하여 충격에 대한 경제 변수들의 반응이 어떠한지를 상세히 비교한다. 추정 결과의 비교를 통하여 내릴 수 있는 결론은, 행동경제학적 가격-책정 모형의 충격반응곡선이 일반적인 뉴케인지안 모형의 충격반응곡선과 상당히 다르다는 점이다. 또한 행동경제학적 모형의 주요 차이점인 가격 변화 확률을 고정시키면 일반적인 칼보 모형과 같은 결과를 얻을 수 있음을 확인한다.

주요어: 행동적 동태확률일반균형; 합당한 가격 책정; 소비자 분노; 이타주의 모수; 칼보 가격 책정; 베이지안 추정.

학번: 2010-23020